FAA ADS - 24

TECHNICAL REPORT

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CRASHWORTHY DESIGN PRINCIPLES

by

D. L. Greer, J. S. Breeden, and T. L. Heid

General Dynamics Convair, San Diego, Calif.

Under Contract No. FA-WA-4583

for

FEDERAL AVIATION AGENCY

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This report has been prepared by General Dynamics/Convair for the Federal Aviation Agency under Contract FA-WA-4583. The contents of this report reflect the views of the contractor who is responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policy of the FAA.

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SUMMARY

This study provides a crashworthy design guide that will improve survivability in moderate to severe crash landings. The objectives of a crashworthy design are: (1) to retain an inhabitable shell around the occupants, (2) to keep the occupants restrained by their seats and the seats attached to the airframe structure, (3) to prevent injury due to local impact, and (4) to ensure means of rapid evacuation.

The portion of the study related to retention of an inhabitable shell includes investigations of primary structure strength, energy absorption, and deceleration capabilities of contemporary transport aircraft. Studies of causes of injuries and fatalities in survivable crashes of modern transport aircraft reveal that current design practices lead to a good crashworthy structure; however, improvements can still be realized by increased fuselage bending strength, redistribution of load carrying materials in the structure, and use of more ductile materials in certain local areas.

Analyses of fuselage axial crushing and wing failure strengths indicate that the structural-collapse energy-absorption capacities of large modern transports are insignficant when compared to the total airplane kinetic energy. Investigation of fuselage vertical crushing strengths is included to provide an indication of the vertical velocities that can be encountered and still retain an inhabitable shell.

The longitudinal decelerations associated with fuselage crushing and wing failure strength capabilities are generally within the range of the present static design requirements for seats and interior equipment. Investigations of the

effects of seat stiffness and slack seat belts indicate that seat failures and occupant injuries are probably more often the result of brittle seat structure, inadequate seat support, and relative velocity between the occupant and seat than of excessive airplane deceleration. The merits of seat ductility and energy absorption capability are discussed.

The portion of the study related to evaluation includes only the effects of structural design considerations. Assurance that the emergency exit doors can be operated after fuselage distortions due to a crash can be provided by reinforcing the framing structure and the operating mechanism.

INTRODUCTION

The purpose of this study is to develop design principles and techniques that will increase passenger and crew survivability in accidents resulting from aborted takeoff, short landings, overshoots, wheels-up landings, and ditchings. The three primary areas of study are: (1) mechanisms of failure and energy absorbing structure, (2) delethalization, and (3) evacuation.

Mechanisms of failure and energy absorbing structure involves the primary airframe structure and the manner in which conventional structures fail under crash loadings, the relative energy levels absorbed by structural collapse, and the airplane decelerations produced during collapse. The objective of this area of study is to improve the airframe capability to retain an inhabitable shell around the occupants.

The objective of delethalization is to improve the occupant retention system and to decrease occupant injury due to local impact with adjacent structure or by loose objects. This area has received considerable attention in the last few years. Seat design, in particular, is showing improvement without significant increase in structural weight.

Investigations in evacuation are limited to the effects of structural integrity on evacuation efficiency. Structural deformation of either the primary airframe structure or interior equipment can affect evacuation. The emergency exit path must be free of obstructions and exit doors must be capable of being operated, even with adjacent structural deformations. Postcrash fire hazards are increased as fuel quantity requirements grow, necessitating improved evacuation efficiency.

1 MECHANISMS OF FAILURE AND ENERGY ABSORBING STRUCTURE

This section deals with the forces and decelerations applied to the airframe and the design principles that must be applied to maintain an inhabitable shell during a crash. The airplane kinetic energy must be dissipated to bring the structure to rest; however, only a small part of this energy can be absorbed by structural collapse. Provisions for allowing local collapse, with the maximum energy absorption, must be employed to prevent destruction of the occupied areas. The magnitude of the decelerations applied to the airframe are a function of the crushing strength of the structure.

1.1 CRASH ENVIRONMENT

Some assumptions regarding crash environment are necessary for a study of the design principles affecting airframe structure. The primary parameters affecting the assumptions are terrain, descent angle, impact attitude, and airplane velocity.

1.1.1 TERRAIN — This parameter is important in determining the causes of structural collapse. Obstacles in the deceleration path and relative hardness of the contact surface will affect the amount and location of damage and the decelerations. When an airplane is sliding level, plowed ground will cause higher deceleration than concrete. With soft ground, the structure can dig in and produce a force that will displace the soil and/or collapse the structure, dissipating energy. The primary energy dissipated is due to soil plowing and compression. There is no plowing on a hard, smooth surface such as concrete. Friction between the structure and surface is the means of dissipating the energy.

The energy absorbed by failure of landing gear, pods and pylons, and portions of the wing and empennage is relatively insignificant with respect to the total airplane kinetic energy; although the longer they remain attached to the airplane, the more protection they give the fuselage and its contents while the airplane is being slowed (absorbing energy) by ground contact. Short-pulse, high-peak accelerations can be alleviated by allowing failure of aircraft parts as the structure strikes ground objects.

Although the energy absorbed by these failures may be relatively small, the kinetic energy of the remaining structure (which forms the protective shell around the passengers) is reduced due to the change in mass.

1.1.2 OTHER PARAMETERS — In addition to terrain factors in crash environment, descent angle, impact attitude, and airplane velocity (Figure 1) affect the survivability of occupants. Descent angle is the direction of motion with respect to the ground and determines the longitudinal, vertical or lateral velocity components. Impact attitude is the relationship of the aircraft axes with respect to the ground and determines the part of the airplane first affected at impact.

Most survivable accidents involve descent angles less than 15 deg. and velocities in the range of those for takeoffs and landings. The vertical velocity component is a limiting factor for most aircraft. Vertical velocity greater than 30 fps will usually cause untenable damage to the fuselage structure, since collapse of the lower shell can damage the passenger floor or reduce the fuselage bending strength until any subsequent longitudinal deceleration will disintegrate the occupied areas. At 100 mph then a descent angle of 12 deg. can be allowed. At 150 mph, the descent angle reduces to 8 deg.

Including an impact attitude adds additional hazards to survivability. A roll attitude can allow a wing to impact first, producing side accelerations and increasing the danger of fuel spillage by crushing the wing fuel tanks or breaking the wing through a fuel tank. Pitch attitude increases the likelihood of breaking the fuselage in the occupied areas.

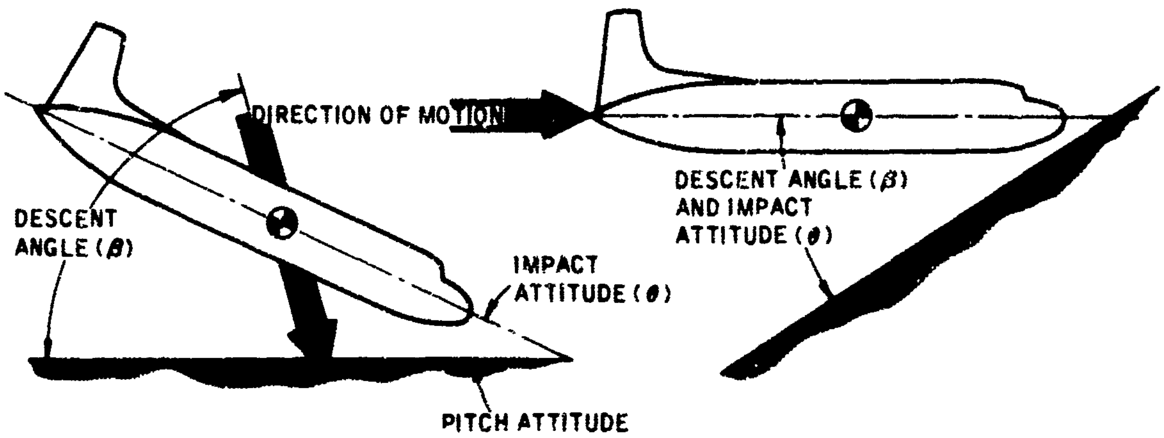

Figure 1. Descent Angle and Impact Attitude

Pitch attitude is not generally appreciable at initial impact on level terrain. It can, however, be a significant factor in survivability with initial impact into a sloped terrain or during subsequent impact into embankments or mounds in the deceleration path. As the airplane encounters these obstacles the nose structure will crush, producing a pitch rotation and translation. If the resulting fuselage bending moments exceed the design moments, failure can occur in the occupied areas.

A study of fuselage bending (Appendix A) indicates that the positive bending moments (compression in the upper shell) produced by the available nose crushing forces can exceed the bending strength requirements of CAR 4. b. Two types of aircraft — a twin-engine, 45,000-lb. transport and a four-engine, 150,000-lb. jet transport — were included in the study.

Two methods of attack are obvious for reducing the possibility of fuselage failure due to nose impact. The nose crushing force can be reduced or the

fuselage positive bending capability increased. An additional study of the same two airplanes (Appendix A, Section A. 2. 5) indicates the desirability of a reasonably strong nose crushing capability. This study assumes an initial impact into a 10-deg. slope with nose crushing forces that will not produce fuselage bending failure. With this assumption, by the time the nose velocity normal to the ground is zero, the airplanes have rotated almost 5 degrees. Nose crushing has not impinged on the occupied areas, but it has severely damaged the forward fuselage section. Increasing the nost crushing force by strengthening the fuselage structure will decrease the initial crushing and rotate the airplane parallel more rapidly.

Increasing the upper shell compression strength will not necessarily require a significant increase in weight. The presently required tension area can be redistributed to increase allowable compression load.

1.2 MATERIALS

Recognition of the "crashworthy" properties of the materials used in aircraft plays an important part in improving survivability in a crash. "Ductility," a prime property, is the capability for energy absorption. A "ductile" material absorbs energy by allowing plastic deformation prior to rupture. A "brittle" material is not capable of plastic deformation and therefore only "stores" energy during elastic deformation.

In the case of deceleration of the entire aircraft in a crash, the kinetic energy is dissipated by friction between the airplane and the ground, plowing the ground by portions of the airplane, and by collapse of the aircraft structure itself. Although the structural collapse energy will not dissipate a very large percentage of the airplane kinetic energy, it is important for secondary reasons.

As the fuselage is attacked by irregularities in the terrain, it is essential that the structure withstand these deflecting loads without affecting the cabin structure. This generally means that the bottom of the fuselage and possibly the forward end will be buckled and crushed by the impact loads Designing these

areas to buckle (ductile) and not tear or rupture (brittle) is essential. A brittle structure will tear away, leaving complete discontinuity while a ductile structure, even though it crushes out of the way, will continue to resist loads and absorb energy during the extreme deformation. The application of the principle of ductility is also important in the design of seat and other passenger accommodation equipment. Peak loads transmitted to the occupants or equipment can be reduced by allowing additional deceleration distance by plastic deformation.

Evaluating an exact measure of ductility is difficult. Elongation is a measure of ductility, but it is not a complete answer to the question. Tear resistance, crack propagation, or stress or strain concentration effect are also needed to determine the material best suited to a crashworthy design. The optimum material is one that has high-strength, lightweight, reasonable elongation up to the rupture strength of the material, continues to hold load even though deformation becomes large, is not notch sensitive, and is free of internal imperfections. Tables A-I and A-II in Appendix A present indications of crack propagation and the toughness properties of various materials.

Brittle fracture is not usually associated with compressive stresses although it is possible. Most compressive failures involve an instability factor that in turn involve bending stresses. Very often the tension stresses produced by the bending are the cause of the brittle fracture.

Materials with a high resistance to crack propagation are generally required for pressurized fuselage skins to meet the demands of fatigue and/or fail-safe requirements. This then is a requirement in favor of crashworthiness. Longerons, fittings, and the larger elements of the structure, however, may not be so restricted and may rupture early in a crash situation. Secondary structure, such as equipment support members or fittings, are usually designed purely from a strength standpoint and may allow local areas of brittle failure that will affect the primary structure. Attention to details may have a great effect on the ultimate crashworthiness of an airplane.

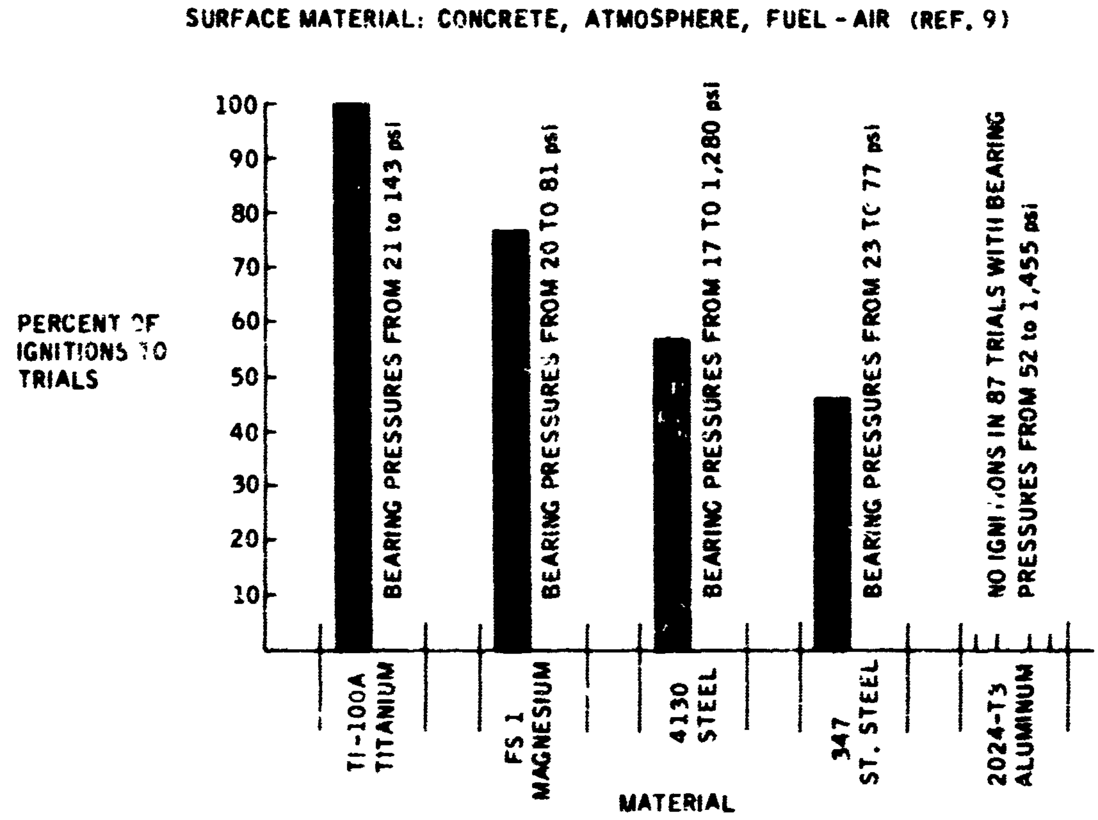

Figure 2. Comparison of Friction-Spark Characteristics of Several Metals (Reference 9)

An additional factor is resistance to spark induction. A material possessing all other necessary attributes, but one that would cause excessive sparks upon contact with rocks, other metal, or concrete may cause more destruction and fatalities than one with lesser attributes. Friction-sparking characteristics of the five commonly used materials are presented in Figure 2. This data was obtained by dragging blocks of the material over concrete or asphalt in an air-fuel mixture of the common aircraft fuels. As shown in the figure, the use of titanium or magnesium in an area where the possibility (or probability) of fuel spillage and ground contact was great could provide an excellent "ignition." Even a minor crash landing could (and has) caused loss of life due to impeded evacuation or rescue (fire blocked exits, cabin fumes, smoke, etc.). If materials exhibiting serious friction-spark or flammable characteristics must be used in susceptible areas fuel containment principles (Reference 36) must be applied to minimize fuel spillage.

1.3 PRIMARY AIRFRAME STRUCTURE

1.3.1 CONFIGURATION EFFECTS — The structural configuration of the lower fuselage shell is an important factor in crashworthiness. This unoccupied structure should be designed to allow crushing or collapse, absorb energy during deformation, and retain fuselage bending and passenger support strength after collapse.

A study of the effects of wing location and probable lower shell collapse for vertical impact is shown in Appendix A, Section A.2.3. Two airplanes are compared — a 45,000-lb. twin-engine low-wing piston-engine transport and a 150,000-lb. low-mid-wing jet transport. Impact is assumed to be in a level attitude, and the effective weight excludes the wing structure, fuel, and engines outboard of the fuselage.

The wing center section of the twin-engine transport protrudes below the fuselage contour and initial impact will crush this structure before the fuselage lower shell is damaged. Using this wing structure collapse distance, the allowable vertical velocity is approximately 21 fps. Level impact at vertical velocities under 21 fps then will not seriously affect the fuselage bending integrity. The maximum vertical deceleration is 10.5g.

Level impact of the jet transport fuselage immediately affects the fuselage bending material, since the wing is inside the fuselage contour by 12 in. Assuming collapse up to the wing lower surface, the allowable vertical velocity is approximately 30 fps and the maximum vertical deceleration is approximately 14g.

From this comparison then, the twin-engine transport configuration is advantageous. The airplane can be decelerated for a reasonable vertical descent velocity without significantly affecting the fuselage bending integrity or producing excessive decelerations. The jet transport impact, however, does affect fuselage bending integrity. Restricting the velocity of the jet to the 21 fps allowed by the twin-engine transport will require a deceleration distance of approximately 6 in. and the maximum deceleration remains 14.3g.

An indication of the collapse effects on fuselage bending strength is shown in Figures A-3 and A-4 (Section A. 2. 1). The 6-in. deceleration distance computed above can reduce the fuselage moment of inertia by 20 to 35 per cent for a conventional arrangement of bending material and more than 50 per cent for an arrangement similar to that at the wing-fuselage intersection of a typical jet transport. If this reduction is produced at initial impact, subsequent decelerations can cause bending failures in the occupied areas.

One method of relieving the effects of lower shell collapse is to provide additional crushing strength to reduce the deceleration distance. This method is not considered advantageous, since the reinforcement not only increases weight but will also increase the deceleration.

A feasible method that will not increase the deceleration or significantly increase the weight is to provide the maximum deceleration distance with the minimum reduction of fuselage bending strength by distributing the lower bending material over a number of widely spaced elements. Figure 3 indicates the concept of material distribution in the area of the wing-fuselage intersection and in the typical fuselage cross-section. Since the vertical crushing strength depends primarily on fuselage beltframes, bulkheads, or other vertical material, the redistribution of longitudinal members will not have an appreciable effect on the collapse strength.

In addition to the improvement for severe vertical impact, the redistribution of lower bending material is an asset during longitudinal decelerations. Local damage can be produced as the fuselage slides over obstacles or is worn away and, if the bending strength is not retained, subsequent decelerations produced by even low normal forces can again cause bending failures in the occupied areas.

Designing the lower fuselage to allow a reasonable deceleration distance presents an additional problem. If the lower fuselage structure is designed to support the passenger seats, collapse of this structure may allow the seats to fail as subsequent decelerations occur. A floor or seat support configuration

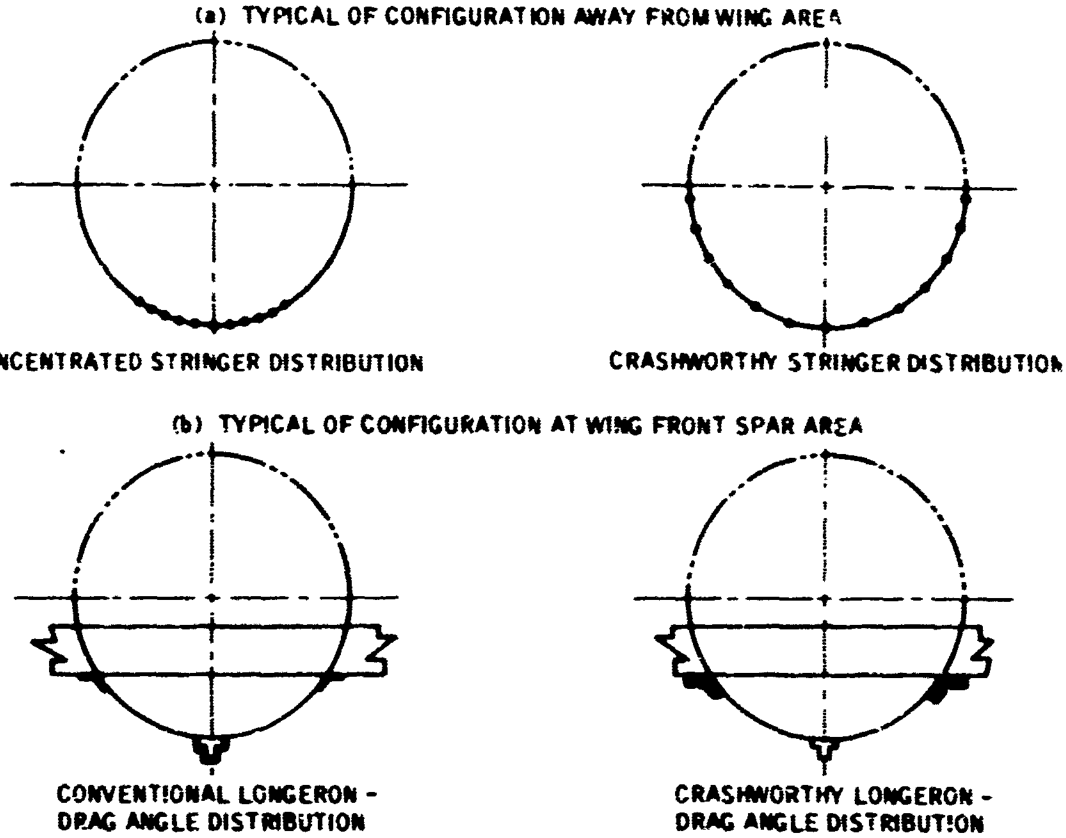

Figure 3. Fuselage Lower Shell Bending Material Distribution

that allows considerable lower shell collapse with negligible loss of strength ..en will increase survivability. Possible results of damage to floor or seat support structure are shown in Figure 4.

The choice of materials used in the lower shell structure can reduce the effects of local crushing or collapse. Ductile materials that deform and crush without tearing or rupture will continue to provide a load path even though they are displaced. Materials of low ductility will tear or rupture and expose additional structure to damage.

1.3.2 ENERGY ABSORPTION AND DECELERATIONS — Just how much energy is absorbed and what are the deceleration magnitudes produced by collapse or failure of the various parts of an airplane? And what are the allowable decelerations of the fuselage? An answer to these questions, along with human tolerances, will provide a basis for determining requirements for seat and equipment

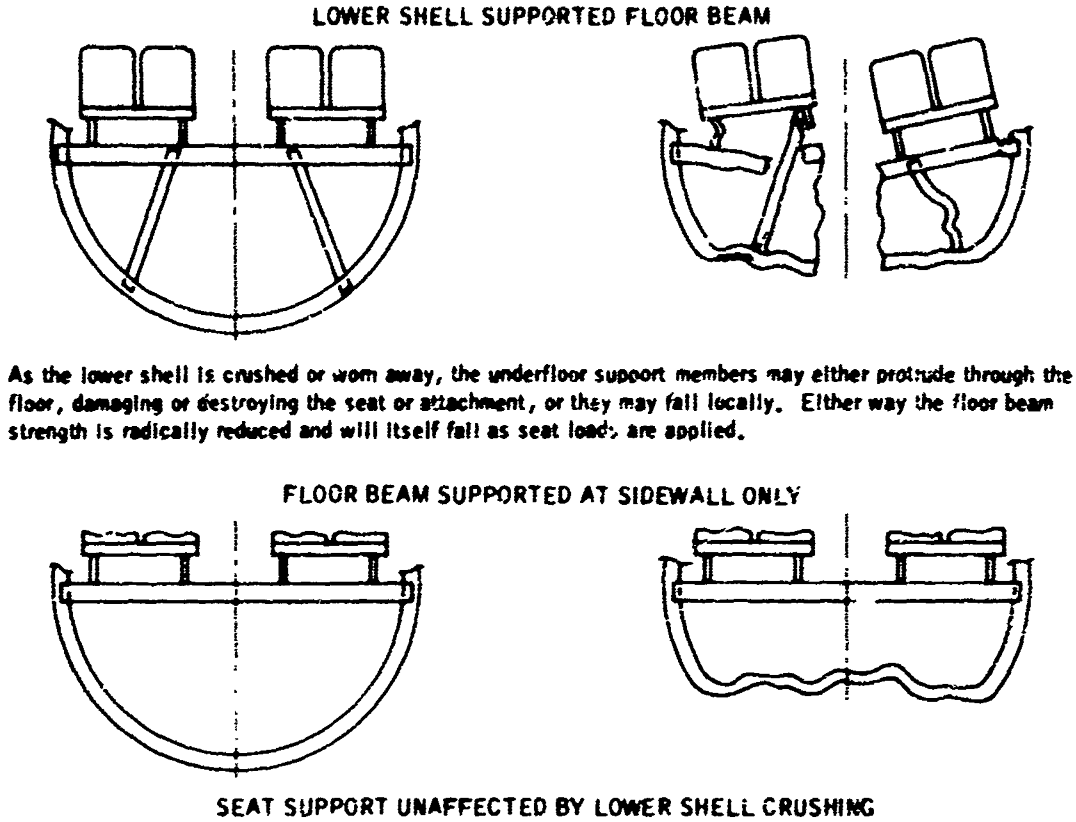

Figure 4. Effects of Under Floor Structure on Survivability

design that will produce the optimum survivability in a crash. Twenty-g seats in a fuselage that will collapse at 10g do not increase survivability. Nine-g seats in a 20g airplane, likewise, will not provide maximum survivability.

As each part of an airplane strikes an obstacle, whether at initial impact or during subsequent motion, kinetic energy and velocity are decreased and decelerations are produced. As the wings strike objects the occupants feel both longitudinal and lateral accelerations, although the course of the airplane may not change greatly. Sections A. 2 and A. 3 include studies of the maximum loads, energies, and decelerations produced as the wings of a twin-engine propeller airplane and a four-engine jet transport are failed in chordwise shear or bending. Several concentrated load application locations are shown for each wing and the crushing distance is conservatively assumed to be one-third the wing depth at the load point. A distributed loading that will fail the wings is also shown.

The maximum wing failing loads shown in Figure A-12, due to local, concentrated impact, are higher than can reasonably be expected since wing local crushing allowables do not approach the shear or bending allowables. Even with this conservatism, the energies absorbed during impact are an insignificant part of the total airplane kinetic energy. Assuming the maximum concentrated wing load the energy absorbed is only 2 per cent per wing for the twin-engine transport at 100 mph and 4 per cent per wing for the jet transport at 150 mph.

The decelerations produced by the inboard concentrated wing failing loads are unrealistic, since neither the wing local crushing allowables nor the loads required to remove most obstacles can approach this magnitude of force. The maximum decelerations normally expected would be encountered during ditching or distributed ground contact. Longitudinal decelerations due to ditching seldom exceed 6g (References 25 and 26).

The lateral accelerations shown in Figure A-13 are produced as one wing impacts an obstacle. These decelerations indicate that it is possible to exceed the static design limit from CAR 4.b, but again since the local wing crushing strength is less than the shear or bending strength, these side acclerations are slightly unrealistic. Side accelerations can, however, exceed the present 1.5g design limit and may be applied after the seats have collapsed.

The work done by axial crushing of the forward fuselage is more significant, in terms of total airplane kinetic energy, than that of wing failure although considerable crushing must occur. Sections A.2.2 and A.3.1 of Appendix A are studies of the decelerations and work produced by fuselage axial crushing, comparing the 45,000-lb. and 150,000-lb. transports, and include the effect of mass reduction on deceleration. The basic assumptions for the analysis include:

a. Only the lower half of the fuselage is effective in crushing. Additional factors such as bending and torsion are partially accounted for by this assumption.

b. The load application is instantaneous and then remains constant.

c. The crushing loads are determined from the skin-stringer column allowables.

With these assumptions, the work done (energy absorbed) by crushing the fuselage forward of the wing front spar accounts for 20 per cent of the total kinetic energy of the 45,000-lb. twin-engine airplane at 100 mph and 8 per cent for the 150,000-lb. jet transport at 150 mph.

Assuming the fuselage forward of the wing front spar destroyed, the maximum deceleration during collapse for the jet transport is 4.2g, including the mass reduction of the fuselage as it is crushed. The effect of additional mass reduction, by assuming the wings, landing gear and engines removed, is shown by the deceleration increase to 11g. The equivalent decelerations for the twin-engine airplane are 6.8 and 18.5g.

Assuming that the airplane is still moving, the deceleration will increase suddenly as the wing center section contacts the obstacle. Survivability in the fuselage over and aft of the wing depends on the ability of this structure to remain intact under the increased loading. An indication of the deceleration allowables of aft fuselage structure is shown in the table on page A-3 with the minimum deceleration of slightly more than 20g for both the twin-engine and jet transports.

These comparisons of energy absorption and decelerations, particularly for a large, fast transport, show that the kinetic energy cannot efficiently be absorbed by structural collapse and still retain a survivable shell. The energy must be dissipated primarily by ground contact and the resulting decelerations usually will not exceed those required by CAR 4.b.

2 DELETHALIZATION

If the fuselage provides a protective shell around the occupants after a crash but the occupants receive fatal injuries inside this shell, survivability has not been improved. The objectives of delethalization are: (1) to provide a means of keeping occupant deceleration within the limits of human tolerance, (2) to retain the occupant in his seat, (3) to keep the seat attached to the airplane structure, and (4) to prevent the occupant from striking adjacent structures or being struck by loose objects and injured.

2.1 OCCUPANT RETENTION

Probably the most significant single contribution to increased delethalization would be assurance that the occupant would remain attached to the seat and aircraft structure during the entire crash period. Only after the occupant has been retained can realistic consideration be given to such things as energy-absorbent padding or structure on all surfaces within flailing distance of the retained occupant, or positive retention of all articles and equipment in the occupied areas.

Occupant retention is of little value if the decelerations applied to the occupant produce major or fatal injuries. Retention with protection against excessive deceleration is a necessity.

2.1.1 PASSENGERS — As indicated by the studies in Appendix A, most survivable transport accidents do not produce airplane longitudinal decelerations of magnitudes that should seriously affect the passengers. Studies in Appendix B, however, show that occupant decelerations do not necessarily coincide with airplane decelerations. The occupant can be subjected to major or fatal injuries, the seat belt

may fail, or the seat attachments may fail at airplane decelerations below the static seat design deceleration.

The factor that probably causes most occupant injuries and seat attachment failures is slack between the occupant and his restraining structure. For longitudinal decelerations slack is produced by a loose seat belt. Vertical slack can be produced with a thick, soft seat cushion. Slack allows a relative velocity to develop between the seat and occupant, producing kinetic energy that must be absorbed by the seat belt, seat, or local fuselage structure. If the restraining structure is rigid and deceleration distance is restricted, occupant deceleration will be magnified. Figure B-1 indicates occupant velocities due to slack that can be attained during low, reasonably long airplane decelerations of 1 to 6g. With a constant 3g airplane deceleration and a 6-in. slack, the relative velocity is approximately 10 ft./sec. Assuming a constant deceleration, if the occupant is stopped in 3 in. his deceleration becomes 9g.

The effects of slack can be relieved (occupant deceleration reduced) by absorbing occupant kinetic energy in the restraining system and allowing additional deceleration distance. The energy that must be absorbed is the energy from the occupant's velocity relative to the seat or floor, not to the ground.

One part of the restraining system that can be used to restrict occupant deceleration is the seat belt. Seat belt webbing elongation can be provided which will allow additional travel and reduce occupant deceleration by storing energy as the belt stretches. The disadvange of this method is that the energy is "stored" and not absorbed, with the possibility that the occupant will be returned to his original position at a substantial velocity. As he is stopped by the seat back, the decelerations produced can fail the seat back and/or cause injury.

Another means of providing deceleration distance and energy absorption is to install energy-absorbing devices (Reference 39) at the seat-belt-to-seat attachment. This type device absorbs energy and provides additional travel by deforming metal or by friction. There is a distinct disadvantage to using this type device

for longitudinal decelerations. It is usually designed for a "one-shot" application and will actually increase slack between the seat belt and occupant after a single deceleration causing its operation. A second disadvantage is the added complexity and weight of the seat structure. A more efficient seat structure may be of greater advantage than adding these devices.

The most efficient method of restricting occupant decelerations is to provide a ductile seat structure that will absorb energy by progressive, plastic collapse. No energy-absorbing devices or mechanisms, other than the seat structure itself, are required and the collapse characteristics can allow more than one deceleration pulse without increasing slack. A study in Appendix B indicates the effectiveness of a ductile seat design when compared to a rigid seat. Assuming the occupant relative velocity is due to a 6-in. slack and that the seat belt webbing will elongate 15%, the rigid seat will be required to support an occupant deceleration of 12g for an airplane deceleration of 4g applied only during the period that the occupant is unrestrained. The ductile seat, however, is designed to deform plastically at occupant decelerations above 9g. Therefore, neither the seat belt nor seat attachment will be required to resist more than the 9g decelerations until the seat has completely collapsed.

The primary consideration in the design of a ductile seat structure is to avoid local areas that will buckle or fail without absorbing energy, allowing the seat to become unattached. The basic structure can be ductile; but local splices, fittings or attachments may not be. Extreme deformations will occur as the seat collapses but the deformation must absorb energy, not release stored, elastic energy; and it must remain attached to the airframe structure for subsequent decelerations. Figure 5 indicates the amount of collapse that can occur and still retain seat attachment.

In addition to relieving occupant decelerations due to relative velocity, a properly designed ductile seat will reduce occupant decelerations due to short pulse, high magnitude airplane decelerations. For all practical purposes the seat

Figure 5. Seat Collapse — Ductile Failure of Forward Leg

should be rigid up to the present design requirements of CAR 4.b (9g forward) and deform above this deceleration. Reference 7, "Seat Design for Crashworthiness," by I.I. Pinkle and E.G. Rosenberg presents a method for determining the seat stiffness requirements for variations in airplane deceleration magnitude and time. Up to 9g, the seat deceleration will coincide closely with the airplane deceleration assuming no slack effects. As the airplane deceleration exceeds 9g the seat will deform, retaining the 9g load and preventing complete loss of occupant restraint.

Two important areas that must receive careful attention with a ductile seat are are the seat-belt-to-seat attachment and the seat-to-airplane attachment. The seat belt attachment must be capable of withstanding suddenly applied loads as the occupant is restrained by the seat belt. Eccentricities and low ductility materials must be avoided. As the seat deforms, the seat legs must not apply a prying load on the local attachment fittings. These local areas can be designed to withstand prying loads, of course, but it usually costs less weight to provide a joint that will avoid prying. Both seat belt and seat attachments should be positively and obviously locked at all times and improper installation should give an obvious warning.

2.1.2 CREW — Providing retention of the crew members of a transport aircraft is more essential than is passenger retention because of the proximity of controls, instrument panels and other hard objects. Structure and/or equipment adjacent to the passengers can be delethalized to avoid serious injury due to local impact.

Crew retention is less difficult, however, since additional restraint can be used. Both a seat belt and shoulder harness should be provided for all crew members.

The principle of providing plastic collapse should be included in the design of crew seats as well as passenger seats. Slack can exist with seat belt and shoulder harness, as well as with seat belt only and occupant decelerations can exceed the static design requirement of the crew seat.

2.2 LOCAL IMPACT

All seat structure which can be contacted by an occupant's body under any flailing position must be covered with energy-absorbent padding or must be shown to be sufficiently yielding so that it can cause only minor injury. At least 2 in. of available displacement is necessary in a seat back for head protection.

Figures 6, 7, and 8 show the results of head impact tests against the top of a deleathalized seat back. This test used a simple pendulum, impacting the dummy head into a fixed seat back. Figures 7 and 8 indicate the amount of deformation that occurs in the structure with the test impact energy of 162 ft.-lb. The maximum head deceleration was 81g (Reference 16) which is considered survivable providing the load is distributed over a reasonable area.

Forward facing seat backs should also incorporate "break-over" features to control the loading by an occupant from behind. Break-over should occur from any position at a seat back deceleration of approximately 2g. Head damage is as dependent on the characteristic of the object struck as on the velocity with which the head strikes the object. However, the importance of seat back break-over can be seen in the

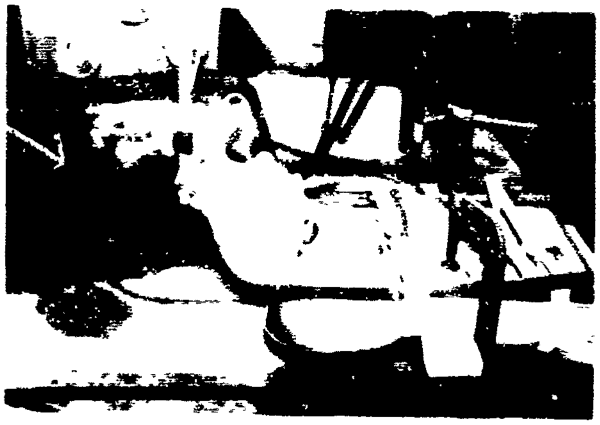

Figure 6. Head Impact Test — Top Edge of Delethalized Seat Back

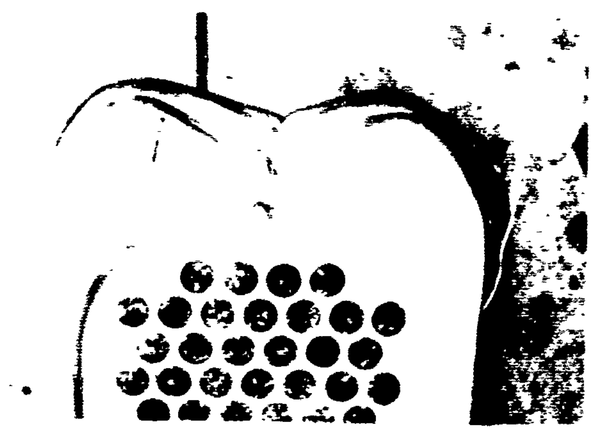

Figure 7. Delethalized Seat Back-Padding Deformation

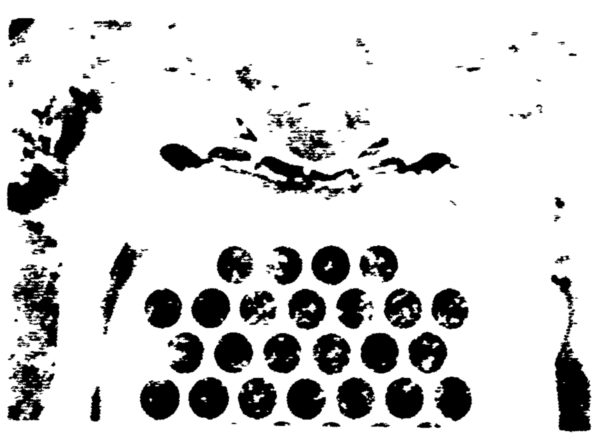

Figure 8. Delethalized Seat Back-Internal Structure Deformation

realization that in a crash, seat deceleration can impart head velocities above 50 fps (Reference Appendix B). Moderate damage to the seat structure should not leave protrusions which could impale the occupants. Sharp, abrupt angles and corners should be avoided and maximum use should be made of smooth, generous radii, especially on seat backs, arm rests and leg shrouds. Edges desired for esthetic purposes should be formed of suitable padding.

2.3 EQUIPMENT RETENTION

It is a virtual necessity that transports provide stowage compartments within the cabin where "carry-on" baggage, packages, etc., can be stowed, thus eliminating unsecured objects in the cabin which could become "flying missiles". These compartments should include doors or other positive retention devices which will preclude the possibility of occupants being struck by projectiles during a survivable crash.

Emergency equipment such as fire extinguishers and portable oxygen bottles must be stowed in a manner which ensures retention. Stowage of this equipment on the aft side of partitions should simplify attaining this objective.

Latches and locks, expecially on galley equipment, must be rugged, simple and obvious in the method of operation. Conscientious effort by designers can improve latches.

3 | EVACUATION

3.1 RELATIONSHIP OF DELETHALIZATION

The inter-relationship of delethalization to evacuation extends beyond the achievement of impact survival. One of the first principles of delethalization — seat retention — is also one of the basic principles necessary for successful evacuation. If seats are not retained, the occupant is not only exposed to the probability of incapacitating impact injuries, but his escape after impact will also be impaired by loose or tumbled seats blocking his path. In the same manner, any other unstowed or unsecured item will not only be a delethalization hazard during impact, but will also interfere with evacuation of the aircraft.

Evacuation considerations should extend into the detail design level of delethalization concepts. That is, energy absorption by means of yielding or controlled progressive collapse of seat structure, while desirable for delethalization improvement, can interfere with evacuation if, in the collapsed position, the seat intrudes into the aisle, blocks access to, or inhibits operation of, an emergency exit. During the detail design, safety devices or principles should be carefully considered for their over-all effects as well as for their performance in the accomplishment of the specific, intended purpose.

Seat belts likewise are primarily a means of achieving delethalization but their details also can effect evacuation. Seat belt buckle design must be such that the belt can always be released normally even after high dynamic loading. without compromising any feature which guards against premature or inadvertent release.

3.2 EXITS

After ensuring the occupant can survive crash decelerations and has access to the emergency exits, consideration must be given to provision of jam-proof exits. Probable structural deflections must be considered at the time of original design of the exit door, operating mechanism, and door framing structure.

The fuselage structure in the vicinity of the door cutout, e.g., skins, frames and longerons around the cutout, should be reinforced over the strength required by the design loads to reduce the possibility of jamming due to structural deformation. The door structure is of less consequence than the framing structure. Clearances between the door and framing structure, however, are important. The probability of door deformation can be reduced if maximum clearance is provided between the heavy structural members of the door and framing structure. Deformation of the framing structure then has less effect on the door operation.

The door operating mechanism should have sufficient strength and mechanical advantage to allow door operation even with nominal binding. The force required for operation should be within the capability of the cabin attendants and the direction of operation should allow the maximum force for opening the door.

3.3 MISCELLANEOUS CONSIDERATIONS

Several factors other than avoidance of aisle blockage and door jamming can affect the efficiency of evacuation. One such factor is emergency lighting which will operate in the survivable areas regardless of damage to other areas. Another factor is evacuation-assist devices (slides, etc.) that operate quickly and easily with automatic compensation for floor-to-ground height.

The hazards associated with post-crash fires must also be considered in improving evacuation efficiency. Part of the hazard is the release of noxious gasses and smoke inside the cabin due to the choice of interior materials and fabrics. Present flame-proofing requirements may not be sufficient qualification for interior materials.

Even external installations can conceivably affect evacuation adversely. An example of this hazard is the presence of vortex generators on the upper wing surface. These blades can affect ditching evacuation in which life raft boarding operation is performed using the overwing exits and the wing upper surface. Obviously, removal of the generators is impractical, but the potential hazard should be recognized.

A review of accident records indicates that airframe skin thickness can influence external fire burn-through time, especially for localized fires of short duration. Thin skins will not dissipate or conduct sufficient heat away from the "hot-spot," allowing rapid burn-through. Thick skins can conduct more heat away from the local area, allow additional time for evacuation and reduce the possibility of interior fires.

4 | WEIGHTS AND COSTS

No appreciable weight or cost increase is necessary to improve survivability in a transport aircraft if consideration is given to crashworthy principles at the preliminary design level.

Improving the fuselage bending strength to ensure nose crushing may require a slight weight increase. Improvement of the positive bending strength of the jet transport used in this study to allow the nose force shown on Figure A-2, would require a weight increase of less than 0.1 percent of the airplane empty weight. Redistribution of lower shell bending material to provide the maximum bending strength after considerable crushing requires a weight increase of even less than that for upper shell strength.

No weight penalty should be necessary in the design of passenger seat support structure independent of the fuselage lower shell if the airplane configuration provides reasonable clearance between the floor and lower shell. Transverse floor beam weight will increase, but this increase if off-set by deletion of vertical or truss supports and reduced requirements for beltframe lower ring strength.

Seat construction using ductile materials should not cause a weight penalty. Seat design incorporating ductile sheet metal construction is usually more expensive than the welded tubular type, but the most efficient deformation characteristics can usually be provided for minimum weight with sheet metal construction.

Equipment tie-down provisions may require a slight weight increase; however, most penalties can be minimized by ensuring ductile attachment rather than by

using "brute-strength" reinforcement. Galley attachments and latches, particularly those in the aft cabin, may require reinforcement to provide retention for decelerations above those presently specified by CAR 4.b.

Overall increase in airplane costs to provide the recommended improvements in crashworthiness should cost no more percentage-wise, than the increase in weight.

CONCLUSIONS

Studies of causes of injuries and fatalities in survivable crashes of modern multi-engine transport aircraft lead to the following general conclusions:

a. Improvements can be made in the crashworthiness of the occupied areas of large transport aircraft with little increase in weight.

b. The materials presently used in the primary aircraft structure are, in general, consistent with crashworthy design. Some local areas can be improved by using a more ductile material to allow larger deformations.

c. Increase in bending strength and redistribution of structural materials would delay failure in the occupied areas as unoccupied areas are crushed and ruptured.

d. Seat and seat support failures are due to dynamic effects, such as those resulting from slack seat belts.

e. A static side load factor of 3g should be used for seat and seat attachment design.

f. Evacuation efficiency is related to, and should be considered with, delethalization.

g. Fuselage deformation adjacent to an emergency exit should be minimized to avoid jamming the exit.

h. Emergency lighting should be available after portions of the occupied areas are failed.

i. Protection against the hazards of crash fires is probably as important as crashworthiness in most survivable crashes.

j. Significant weight or cost increase is not necessarily a requirement for increased survivability. Recognition and use of crashworthy design principles in initial design can minimize both weight and cost factors.

DESIGN GUIDE

PRIMARY AIRFRAME STRUCTURE

a. Provide a fuselage bending strength that will withstand the bending moment produced by nose crushing. Compression in the upper shell is usually critical.

b. Disperse the lower fuselage bending material over a number of widely spaced elements to retain bending strength with partial failure or collapse of the lower shell.

c. Design the passenger floor structure to retain its strength after the fuselage shell below the floor support structure has been crushed or ruptured.

d. Use ductile materials, exhibiting high tear resistance for the lower fuselage shell structure.

e. Avoid use of materials with friction-sparking characteristics in areas subject to ground contact.

f. Apply fuel containment principles to fuel tanks.

g. Use thick-skin construction to increase burn-through time in case of post-crash fire.

DELETHALIZATION

a. Use ductile seat construction to allow plastic, energy absorbing collapse at occupant decelerations above those presently required. After seat collapse the seat should remain attached to the airframe and be capable of restraining the occupant for longitudinal decelerations of up to 12g.

b. Provide energy-absorbent padding or yielding structure on all areas that can be struck by an occupant.

c. Design the seat back to "break-over," from any initial position, at approximately 2g.

d. Provide positive retention of all carry-on articles as well as aircraft equipment.

EVACUATION

a. Design the fuselage structure around doors overstrength to minimize the possibility of a failure jamming the door.

b. Provide as much clearance as possible around doors and design door mechanisms with sufficient mechanical advantage to allow operations in case of nominal binding.

c. Provide an emergency lighting system that allows operation in the survivable areas regardless of other damage.

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APPENDIX A | PRIMARY AIRFRAME STRUCTURE

A.1 MATERIALS

The material property emphasized in this study is ductility; however, several measures of ductility are avilable, with no one measure providing a complete definition. Tear resistance and toughness are terms of ductility measurement. Each is discussed in detail below.

A.1.1 TEAR RESISTANCE — This term is used to define the energy levels required to propagate a crack. Table A-I presents test data on the tear resistance of the commonly used aluminum alloys. The values presented are for thin gage (0.063) sheet material using a Kahn type test specimen. Recent tests indicate that tear resistance decreases markedly as thickness increases. The relationship between alloys, however, is apparently unchanged. Note that tear resistance and elongation are not necessarily consistent in determining ductility.

A.1.2 TOUGHNESS — This term, derived from load deformation curves, can also be applied as a measure of ductility. The principal requirement for computation of this value is that the material must have a definite plastic deformation characteristic. Allowance can be made for the presence or lack, of a definite yield point with use of the following equations (Reference 12).

For a material with a definite yield point:

$$\text{Toughness} = \left(\frac{F_{ty} + F_{tu}}{2}\right)\left(\epsilon_u\right)\left(K\right)$$

For a material witnout a definite yield point:

$$\text{Toughness} = \left(\frac{2\,F_{tu}}{3}\right)\left(e_u\right)\left(K\right)$$

...stant for specimen cross section and length.

Table A-II presents the relative toughness values, computed by these equations, for materials commonly used in aircraft.

A.2 AIRFRAME STRENGTH STUDY

A.2.1 FUSELAGE BENDING CAPABILITY — Figures A-1 and A-2 present a comparison of the fuselage bending moments obtained using civil air regulations and the moments produced by the force required to crush the fuselage nose during a crash landing. Included are the allowable bending moments determined by the section data and allowable compression stresses. Two types of transport aircraft are shown. Figure A-1 is for a twin-engine piston airplane and Figure A-2 is for a four-engine jet. The bending moments produced by nose crushing include both translation and rotation inertia relief.

Figures A-1 and A-2 assume that the fuselage bending material is ...act and show that the bending produced by a force at the nose can exceed both the required and allowable positive moments in the occupied areas of the fuselage. Figures A-3 and A-4 show the reduction in section moment of inertia as the lower fuselage material is lost due to collapse or local damage.

Figures A-5 and A-6 indicate the magnitudes of vertical acceleration that is produced by both rotation and translation for various nose crushing forces.

A.2.2 FUSELAGE AXIAL CAPABILITY — Figure A-7 is a comparison of axial crushing strengths of a twin-engine piston airplane and a four-engine jet transport. The assumptions made in determining these values include:

a. Only the lower half of the fuselage is effective in crushing and only axial load is considered. Additional factors which would contribute to failure, such as bending and torsion, are partially accounted for by this assumption.

b. The load application is instantaneous and then remains constant. Since the crushing load at each station is determined by the column allowables of the skin-stringer elements, both dynamic "overshoot" on column allowable and internal dampening throughout the aircraft will tend to support this allowable column load assumption.

c. Total collapse, back to the wing front spar, is allowed.

From the forward fuselage crushing strength allowables, Figures A-8 and A-9 present a comparison of the magnitudes of longitudinal deceleration produced during crushing. The effect on deceleration, as mass is reduced by crushing, is included in the curve labeled "intact airplane". Additional mass reduction as landing gear, engines and wings are torn away, increases the decelerations applied to the remaining, occupied portion of the fuselage.

The table below shows, for the airplanes under study, the crushing load and resultant deceleration allowables of the fuselage structure aft of the wing.

	TWIN ENGINE		FOUR ENGINE JET	
	CONFIG. A	CONFIG. B	CONFIG. A	CONFIG. B
CRUSHING LOAD	251,000 LB.		670,000 LB.	
ALLOW. DECEL.	21g	28g	21.5g	29g

The crushing load capability assumptions are identical to those of the forward fuselage analysis. The mass affecting deceleration includes two passenger-cargo loading configuration. Configuration "A" assumes the aft fuselage is loaded to full capacity. Configuration "B" assumes a one-half capacity load.

A.2.3 FUSELAGE VERTICAL CRUSHING CAPABILITY — A comparison of the forces required to crush the lower structure of a twin-engine transport with the wing center section protruding below the fuselage contour, and of a four-engine jet with the wing inside the fuselage contour, is shown on Figures A-10 and A-11. The analyses assume impact in a level attitude and include only the structure within the fuselage boundary.

The crushing forces for each item of structure are determined primarily by the compression strength although web shear and frame or beam bending are applicable in some areas. The materials are assumed to be ductile and the collapse force is constant throughout the deformation.

Using the "allowable" collapse distance and crushing forces shown on Figures A-10 and A-11, the maximum vertical velocity can be determined from the equation $V^2 = 2\ a\ s$. Assuming that the weight of the wing, fuel, and engines outboard of the fuselage are supported by the nacelles or pod-pylons, the effective airplane weights are: 20,000 lb. for the twin-engine transport and 70,000 lb. for the four-engine jet. The maximum vertical velocites then, are 21 ft./sec. and 30 ft./sec., respectively.

Assuming the same effective weights for the maximum decelerations, the twin-engine airplane will produce 10.5g and the jet transport will produce 14.3g.

A.2.4 WING STRENGTH CAPABILITY — Figures A-12 and A-13 presents the magnitudes of concentrated aft load required to cause chordwise shear or

bending failure of contemporary transport wings. The loads, although indicative of overall wing strength, may not be obtainable since:

a. Wing structure is seldom strong enough to sustain local concentrated loads of the magnitudes shown.

b. Few obstacles in crash path can present such concentrated resistance.

Included in Figures A-12 and A-13 are the magnitudes of distributed impact load required to fail the wings. Both full span and half span magnitudes are shown.

Figure A-14 presents the magnitude of side accelerations produced by the maximum concentrated wing failure impact force for the twin-engine transport. These side accelerations assume that the force is applied to only one wing and that the structure is rigid.

A.2.5 PITCH IMPACT STUDY — The purpose of this study is to provide an indication of the amount of pitch rotation and forward fuselage crushing that can be expected during a crash that involves a nose-down attitude. The analyses use the physical properties of two existing aircraft; a twin-engine transport with a gross weight of 45,000 lb. and a four-engine jet transport with a gross weight of 150,000 lb.

The initial assumptions are:

a. A gear-up configuration impacting in a nose-down attitude of 10°.

b. Only the force normal to the ground affects rotation.

c. Fuselage bending deflection is negligible.

d. The nose crushing force and pitching moment is constant.

e. Initial descent velocity is limited to that allowed by level impact (Reference Section A.2.3).

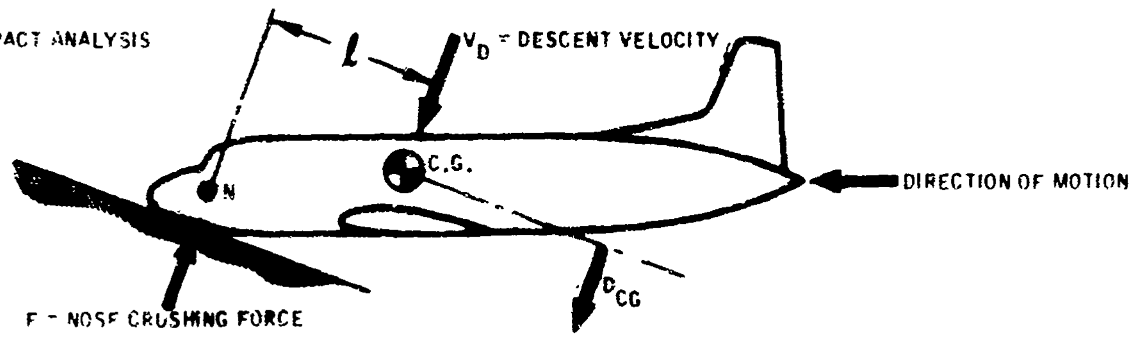
f. The nose crushing force is that allowed by the existing fuselage bending strength (Reference Section A.2.1).

g. Nose crushing stops as the velocity of a point in the nose becomes zero.

The results of the study are indicated on Figures A-15 and A-16. With the assumptions made the airplanes are not rotated level by the time the descent of the nose is stopped. The descent velocity at the airplane cg does, however, reduce and the nose structural collapse does not necessarily affect the occupied areas.

The rotation and collapse produced will probably allow any additional crushing to be resisted by the wing or underwing structure.

PITCH IMPACT ANALYSIS



Just prior to impact $V_{CG} = V_N = V_D$

at the assumed final condition $V_{CG} = (V_D - at)$, $V_N = 0$

and $V_N = V_D - at - \omega\ell = 0$

giving: $V_D = t\left(\frac{Fg}{G.W.} + \frac{F\ell^2}{I_0}\right)$

or $t = \dfrac{V_D}{\dfrac{32.2F}{G.W.} + \dfrac{F\ell^2}{I_0}}$

The distance the CG will travel, $D_{CG,} = V_D t - \frac{at^2}{2}$

and the distance the nose will crush, $S_{CR.}, = \frac{V_D t}{2}$

The rotation, then, $\phi = \sin^{-1}\left[\frac{D_{CG} - S_{CR.}}{\ell}\right]$

$$= \sin^{-1}\left[\frac{V_D t - \frac{32.2\,F\,t^2}{G.W.}}{2\ell}\right]$$

A.3 ENERGY ABSORPTION CHARACTERISTICS

As portions of the airplane are crushed, collapsed or otherwise failed during a crash landing, part of the airplane kinetic energy is absorbed. This portion of the study provides an indication of the magnitudes of work produced by the crushing and collapse forces, and corresponding deformation distances.

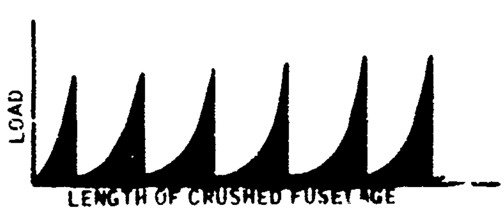
A.3.1 FUSELAGE AXIAL COLLAPSE — The work produced by fuselage axial crushing is equal to the area under the load deformation curves of Figure A-7. Collapse is assumed to be plastic, with the collapse force instantaneous and constant for each increment of length.

The work, then, equals:

a. 3,200,000 ft.-lb. for the twin-eingine airplane.

b. 9,000,000 ft.-lb. for the four-engine jet transport.

If the collapse is not plastic (the configuration or materials allow brittle failures) the load-deformation curve produced will appear similar to that shown below.



Using the collapse load data for the jet transport, the work produced (area under the load-deformation curve) reduces to approximately 2,000,000 ft.-lb. In addition to the reduced energy absorption capability, the decelerations produced will be a series of abrupt peaks as the structure ruptures or breaks.

A.3.2 FUSELAGE VERTICAL COLLAPSE — As in the case of work produced by axial crushing, the forces required to collapse the lower fuselage structure vertically are assumed to be instantaneous and constant, signifying ductile and plastic failure. A limiting assumption is included in this analysis in an attempt to avoid collapse that would seriously damage the passenger floor. Considerable energy can be absorbed by vertical crushing if no consideration is given to the integrity of the occupied portions of the fuselage.

The available work (from Section A.2.3). is then:

a. 210,000 ft.-lb. for the twin-engine airplane (assuming a collapse distance of 1 ft.).

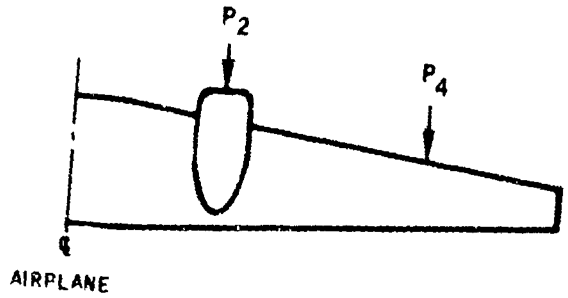
b. 1,500,000 ft.-lb. for the jet transport (assuming a collapse distance of 1-1/2 ft.).

A.3.3 WING CHORDWISE STRENGTH — The maximum wing chordwise load capabilities, as noted in Section A.2.4. are extremely optimistic for use in determining actual decelerations or energy-absorption values. However, these maximum loads are used for comparison with airplane kinetic energies. The following examples indicate the work produced as the impact loads crush the wing at various stations. The crushing depth, prior to complete wing failure, is assumed to extend into the wing a distance equal to one-third of the structural box chord at the point of impact.

Example I — 45,000 lb. gross weight twin-engine transport.

V = initial velocity = 150 ft./sec.

Kinetic Energy = 15,700,000 ft./lb.



Inboard Load (P_2) = 237,000 lb./side (Reference Figure A-12)

Box Depth = 4 ft.

Crushing Energy = 315,000 ft.- lb. or 2% of the kinetic energy

Outboard Load (P_4) = 43,000 lb./side (Reference Figure A-12)

Box Depth = 2.4 ft.

Crushing Energy = 34,400 ft.- lb. or 0.22% of the kinetic energy

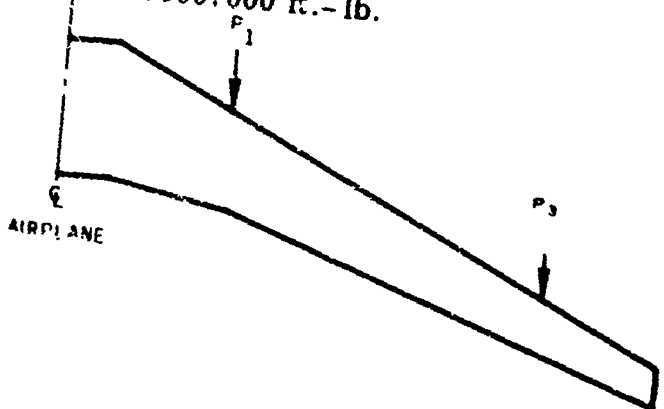
Although the crushing energy is not a significant part of the kinetic energy, the remaining occupied structure does benefit by the failure. The mass of the remaining structure is reduced, which reduces the kinetic energy.

Assuming the inboard load reduces the weight by 10,000 lb./side (wing structure and fuel) the kinetic energy of this mass is 3,500,000 ft.-lb. or 22% of the initial total kinetic energy.

Example II — 150,000 lb. gross weight jet transport

Initial Velocity = 220 ft./sec.

Kinetic Energy = 113,000,000 ft.-lb.



Inboard Load, (P_1) = 1,130,000 lb. (Reference Figure A-13).

Box Depth = 12 ft.

Crushing Energy = 4,500,000 ft.-lb. or 4% of the kinetic energy.

Outboard Load, (P_3) = 206,000 lb. (Reference Figure A-13).

Box Depth = 5 ft.

Crushing Energy = 343,000 ft.-lb. or 0.3% of the kinetic energy.

The energy reduction due to mass loss is again significant. Using the inboard load, the weight loss is approximately 40,000 lb./side. The energy of this mass then, is 30,000,000 ft.-lb. or 26.5% of the initial total kinetic energy.

A.3.4 KINETIC/POTENTIAL ENERGY RELATIONSHIPS — The work done (energy-absorbed) in the various modes of structural collapse shown in the preceding paragraphs is of interest primarily when compared to the kinetic energy that must be dissipated during a crash landing. Figure A-17 provides the range of kinetic energies that must be dissipated during crashes of airplanes with gross weights from 20,000 to 200,000 lb. The maximum velocity in this figure is limited to 220 ft./sec. The velocities from 10 to 50 ft./sec. are indicative of the vertical component produced by descent angle.

A.4 CRASH SEQUENCE ANALYSIS

Using the data obtained in the preceding paragraphs, a crash sequence analysis is made for the jet transport (Figure A-18). The assumed sequence, does not necessarily produce the most critical decelerations that can be obtained but it does indicate the relative value of structural collapse in bringing an airplane to rest in a crash situation.

The initial assumptions include:

a. Impact velocity = 150 mph (220 ft./sec.).

b. Descent angle = Level

c. Level impact attitude.

d. Combined friction/plowing coefficient = 0.30.

Table A-I. Tear Resistance and Ductility of Aluminum Alloys (Ref. 15)

Material		Longitudinal				Transverse			
		F_{tu} (psi x 10^{-3}) (Test Specimen Properties)	F_{ty} (psi x 10^{-3}) (Test Specimen Properties)	Elong. (%) (Test Specimen Properties)	Tear Res.* (in.-lb./in.^{2})	F_{tu} (psi x 10^{-3}) (Test Specimen Properties)	F_{ty} (psi x 10^{-3}) (Test Specimen Properties)	Elong. (%) (Test Specimen Properties)	Tear Res.* (in.-lb./in.^{2})
2014	T6	71,600	65,700	10.4	250	71,000	63,600	10.0	180
2020	T4	50,000	34,200	16.5	1,110	49,400	31,600	16.5	1,060
2020	T6	82,000	77,500	7.4	30	81,800	75,400	7.0	15
2024	T4	69,700	48,200	20.3	705	67,500	45,200	19.8	610
2024	T3	69,600	52,400	19.5	710	67,400	46,400	19.7	600
2024	T36	75,100	63,600	15.1	425	73,400	56,400	15.0	385
2024	T6	67,200	53,200	9.5	275	66,300	51,800	8.8	245
2024	T81	74,200	69,800	6.6	170	73,600	69,000	6.1	150
2024	T86	77,100	72,400	6.4	125	76,100	71,200	6.1	115
2219	T4	55,400	37,000	21.0	1,460	55,700	33,600	19.5	1,300
2219	T87	69,700	57,700	9.5	235	70,000	57,600	9.4	295
2618	T6	61,300	56,200	6.2	270	60,600	54,200	6.0	235
7075	T6	82,300	74,900	11.2	290	82,300	72,500	10.8	220
7075	T73	71,600	60,300	10.6	510	72,900	61,000	10.3	400
7079	T6	76,000	68,600	10.9	510	75,900	66,600	10.8	370
7178	T6	88,800	80,900	12.2	140	88,000	77,600	11.9	130

*Unit Tear Propagation Energy Using the Kahn Tear Test

Note: The values presented are for thin gage (0.063) sheet material. Recent tests indicate that tear resistance decreases markedly as thickness increases. The relationship between alloys, however, is apparently unchanged.

Table A-II. Metal "Toughness" Based on Ultimate Tensile Stress and Elongation (Ref. 12)

Material		Properties (MIL-HDBK-5)						Toughness
		Longitudinal			Transverse			Long.
		F_{tu} (psi x 10^{-3})	F_{ty} (psi x 10^{-3})	Elong. (%)	F_{tu} (psi x 10^{-3})	F_{ty} (psi x 10^{-3})	Elong. (%)	(in.-lb.)
Alum. Sheet								
t = .063 to .249								
2014	T6	68	60	8	67	69	8	3,620
2020	T6	76	70	4	76	70	4	2,020
2024	T3	65	48	15	64	42	15	6,500
2024	T42	62	40	15	62	40	15	6,200
2024	T36	70	60	12	69	52	12	5,600
2024	T81	67	59	5	65	56	5	2,230
7075	T6	77	67	8	77	66	8	4,100
7079	T6	73	63	8	73	63	8	3,890
7178	T6	84	74	8	84	74	8	4,480
2219	T4	55	37	21	55	34	19	7,700
Alum. Extr.								
2014	T6	60	53	7	60	53	5	2,800
2024	T4	57	42	12	57	42		4,560

Table A-II. Metal "Toughness" Based on Ultimate Tensile Stress and Elongation (Ref. 12) (Continued)

Material		Properties (MIL-HDBK-5)						Toughness
		Longitudinal			Transverse			Long.
		F_{tu} (psi x 10-3)	F_{ty} (psi x 10-3)	Elong. (%)	F_{tu} (psi x 10-3)	F_{ty} (psi x 10-3)	Elong (%)	(in. -lb.)
2024	T42	57	38	12	50	36		4,560
7075	T6	78	70	7	76	64	5	3,640
7079	T6	75	67	7	73	65	6	3,500
7178	T6	84	76	5	81	71		2,800
Alum. Castings								
195	T4	29	13	6				1,160
195	T6	32	20	3				640
356	T6	33	22	3				660
C355	T61	41	31	3				820
A356	T61	38	28	5				1,270
220	T4	42	22	12				3,360
Steel								
1025		55	36	22	55	36	22	10,000
4130 98BV40N		90	70	17	90	70	17	10,200
Alloy Steel		125	103	23	125	103	23	26,200

Table A-II. Metal "Toughness" Based on Ultimate Tensile Stress and Elongation (Ref. 12) (Continued)

Material	Properties (MIL-HDBK)						Toughness
	Longitudinal			Transverse			Long.
	F_{tu} (psi x 10^{-3})	F_{ty} (psi x 10^{-3})	Elong. (%)	F_{tu} (psi x 10^{-3})	F_{ty} (psi x 10^{-3})	Elong. (%)	(in. -lb.)
Alloy Steel	180	163	15	180	163	15	25,700
Alloy Steel	260	217	10	260	217	3	23,800
301 Stainless	125	75	25	125	75	25	20,800
301 Stainless	185	140	9	185	140	9	11,100
350 Stainless	165	135	10	165	135	10	11,000
17-4 PH Bar	190	170	10	190	170	10	12,600
17-7 PH Sheet	180	150	6	180	150	6	7,200
Titanium							
4AL-4MN Bar	140	130	12				11,200
6AL-4V Bar	130	120	10				8,670
6AL-4V Sheet	130	120	8	t less than .070			6,940
6AL-4V Sheet	130	120	10	t greater than .070			8,670
Magnesium							
AZ31B Sheet (H24)	39	29	6	40	32	8	1,560
AZ31B Extr.	35	21	7				1,630

Table A-II. Metal "Toughness" Based on Ultimate Tensile Stress and Elongation (Ref. 12) (Continued)

Material	Properties (MIL-HDBK-5)						Toughness
	Longitudinal			Transverse			Long.
	F_{tu} (psi x 10^{-3})	F_{ty} (psi x 10^{-3})	Elong. (%)	F_{tu} (psi x 10^{-3})	F_{ty} (psi x 10^{-3})	Elong. (%)	(in.–lb.)
AZ61A Extr.	38	21	8				2,020
AZ63A Cast. (F)	24	10	4				1,600
AZ63A Cast. (T4)	34	10	7				1,590
AZ63A Cast. (T5)	24	11	2				320
AZ91C Cast. (T4)	34	10	7				1,590
AZ91C Cast. (T6)	34	16	3				680

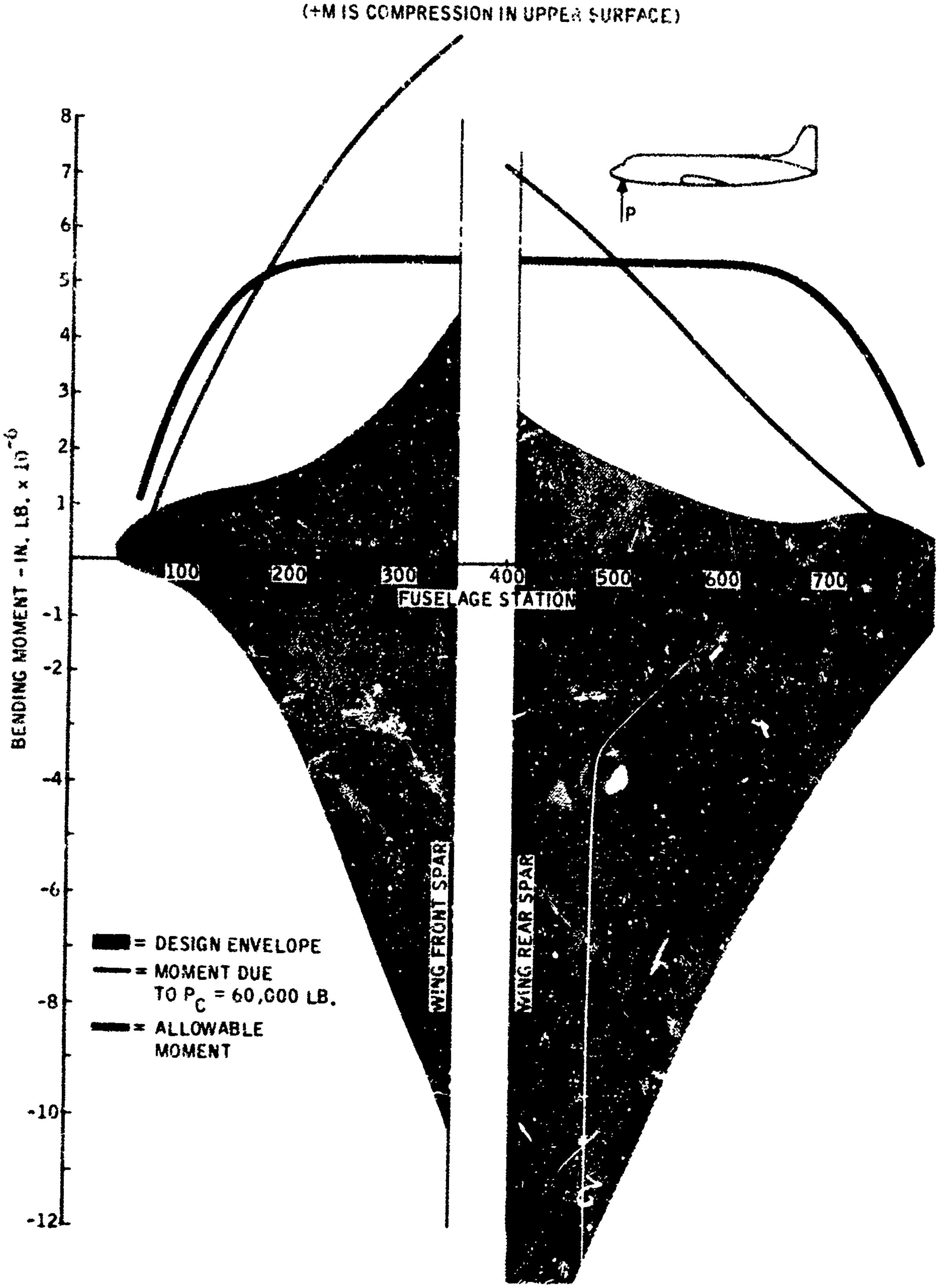


Figure A-1. Fuselage Bending Moment — Twin-Engine Transport

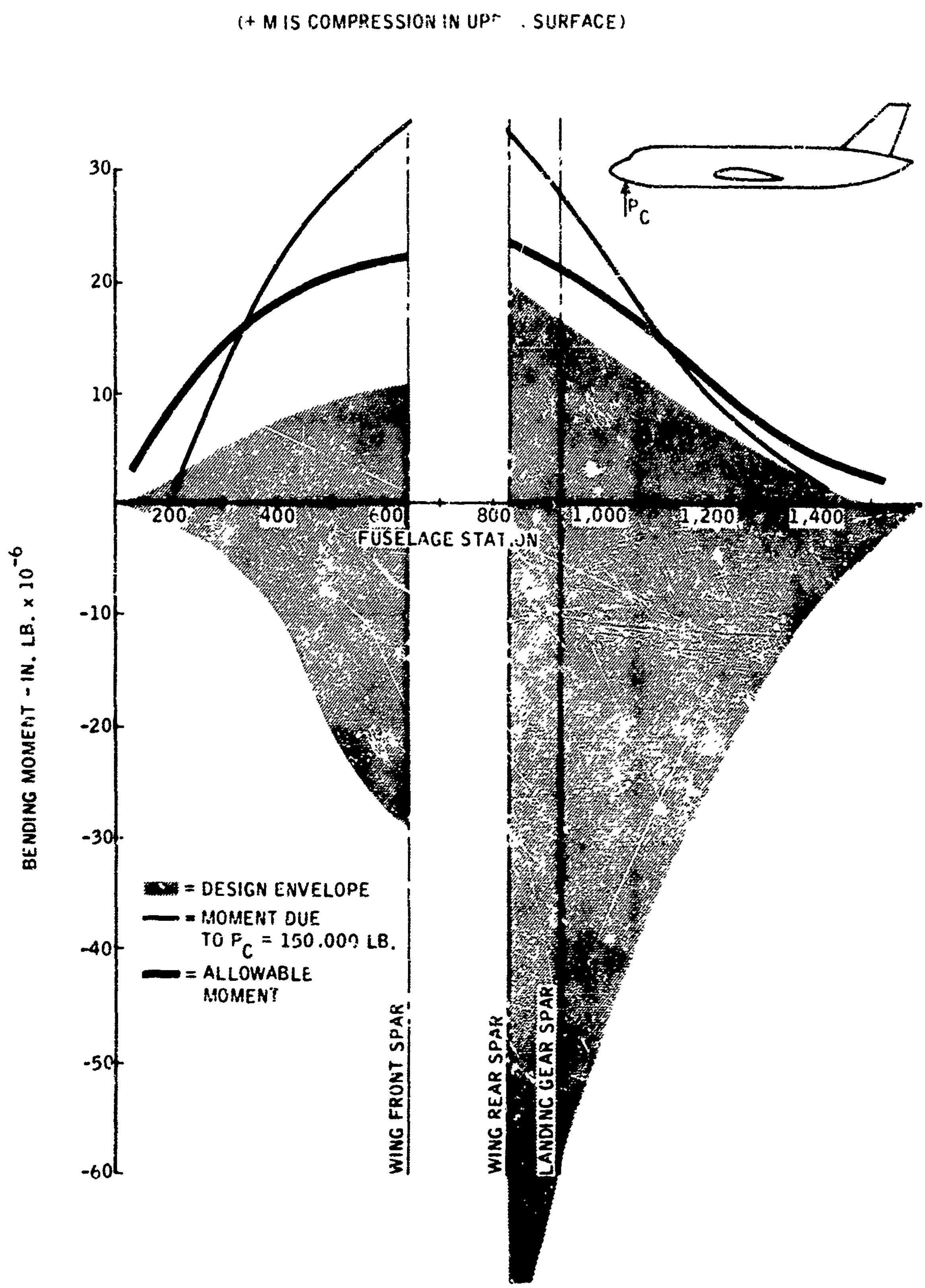


Figure A-2. Fuselage Bending Moment — Four-Engine Jet Transport

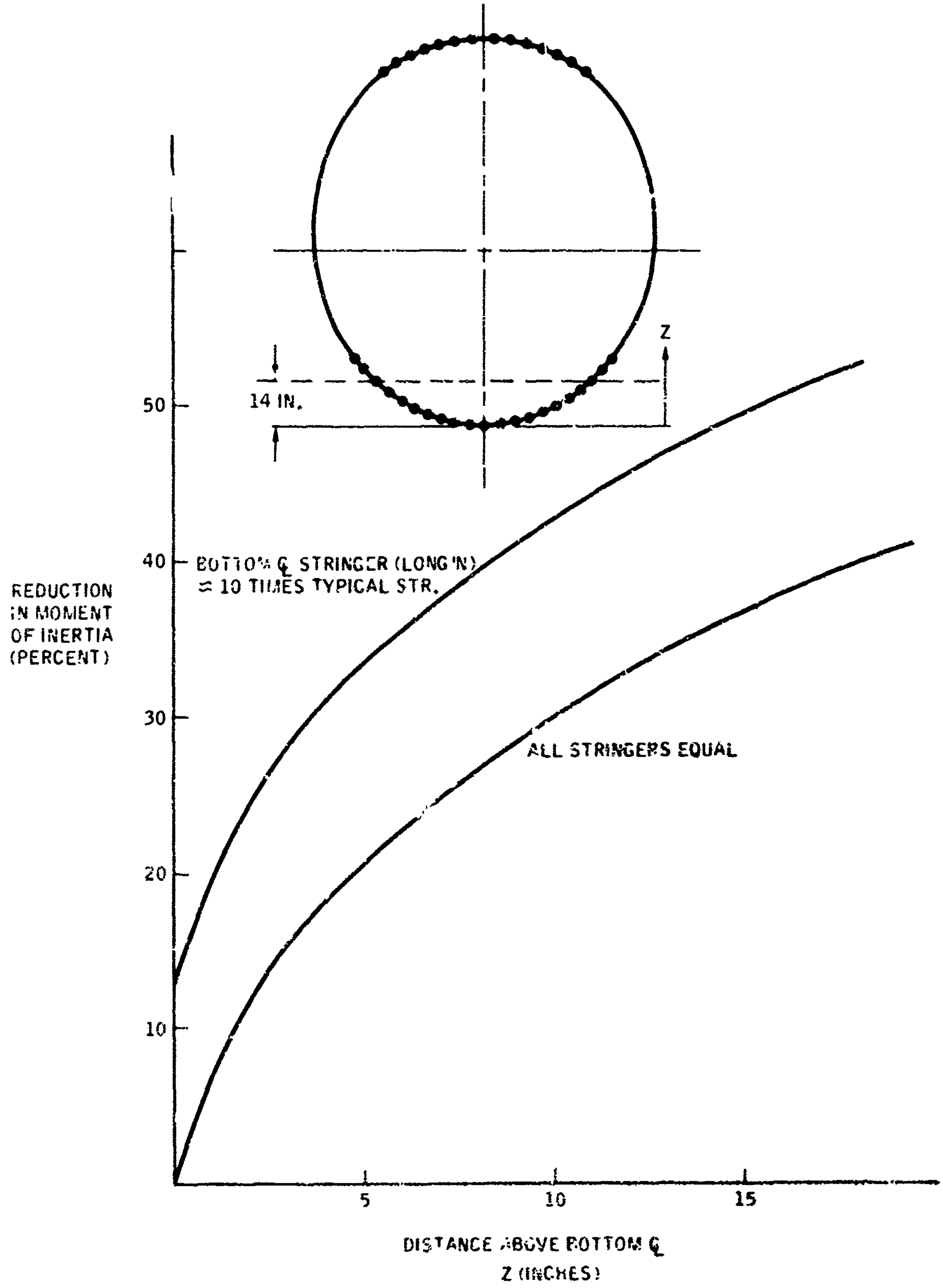


Figure A-3. Typical Fuselage Fwd and Aft of Wing Reduction in Bending Moment of Inertia Vs. Crush Height

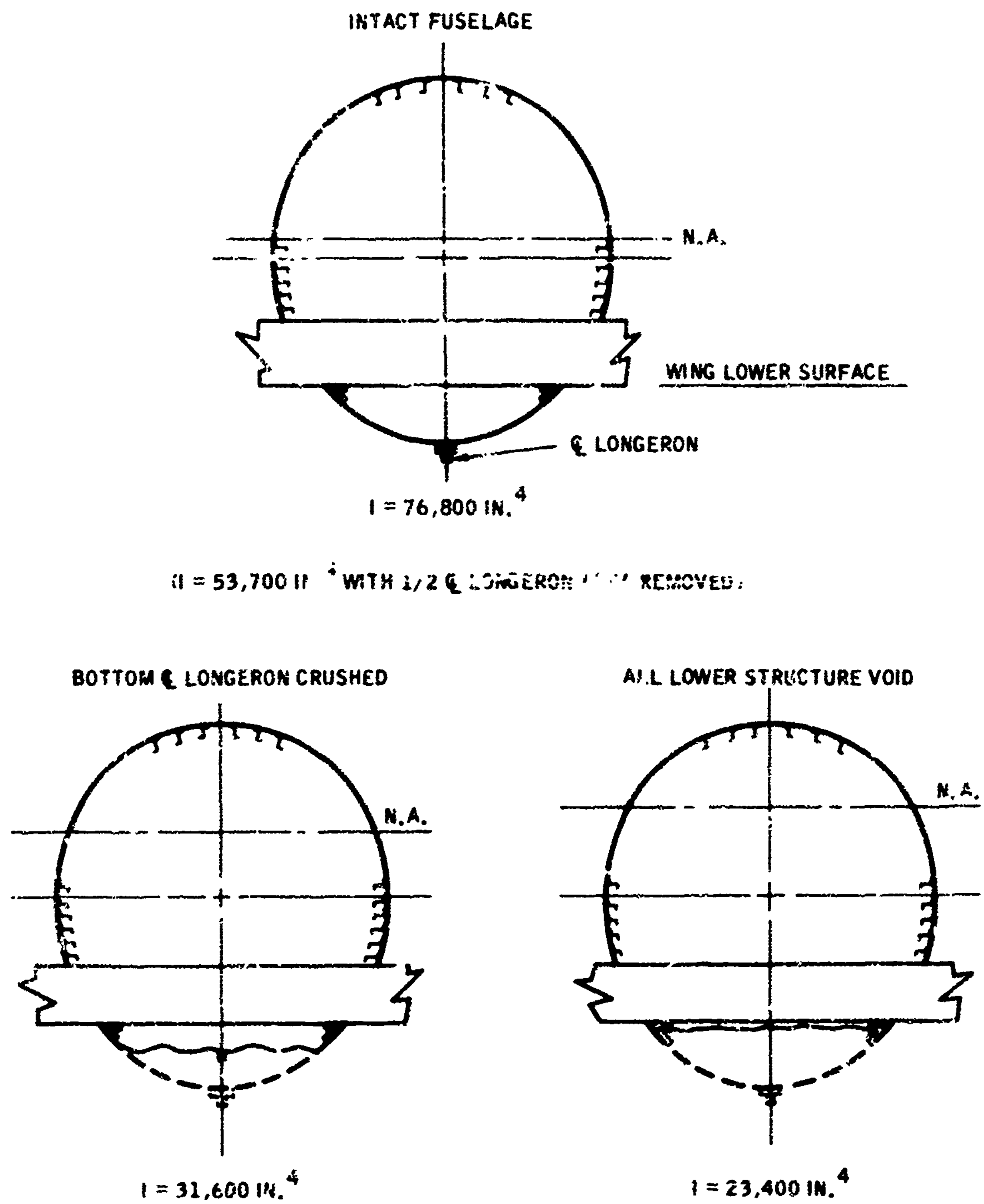


Figure A-4. Fuselage in Wing Area Variation in Fuselage Section Data With Loss of Primary Bending Members

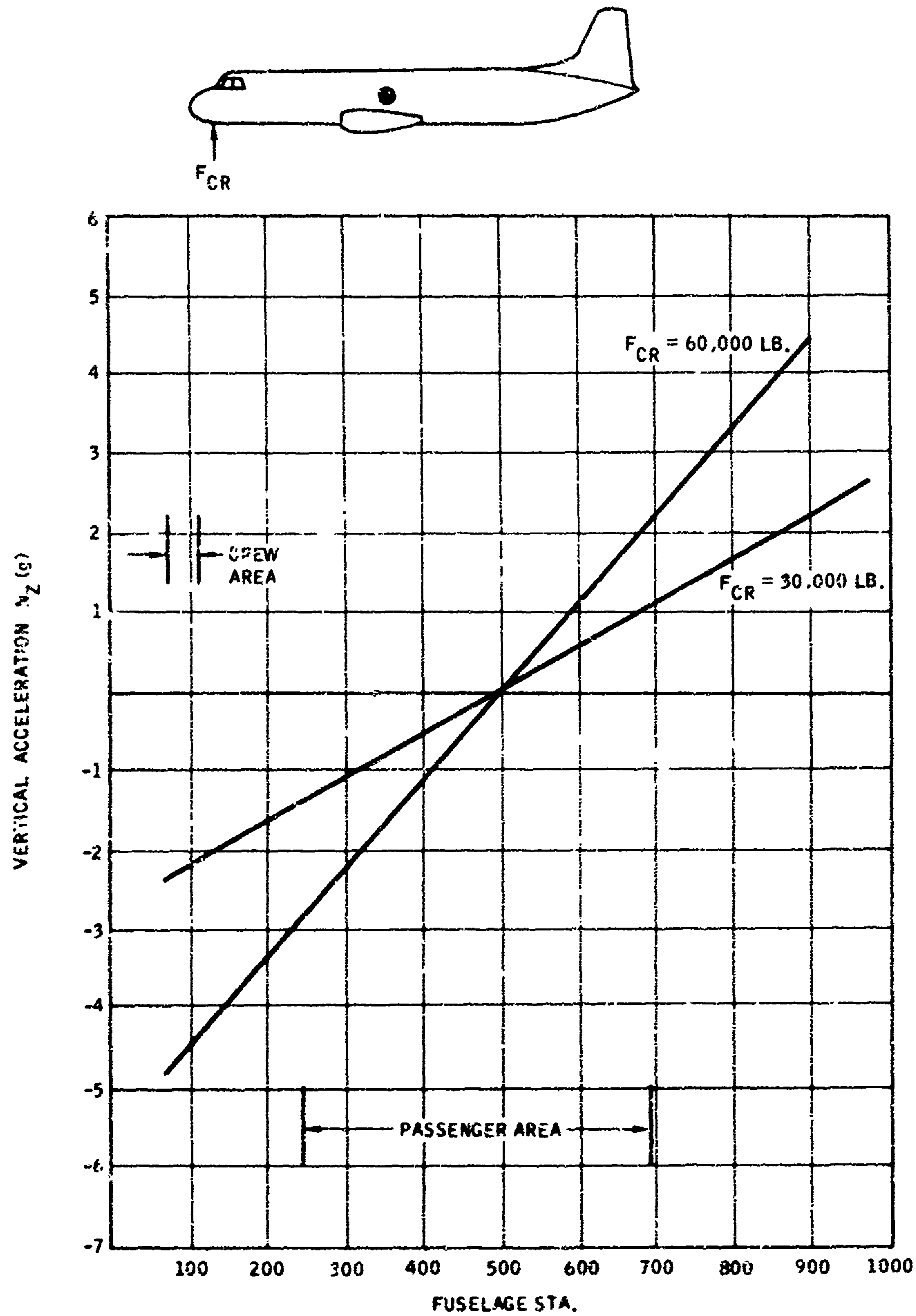


Figure A-5. Vertical Acceleration Due to Nose Crushing Forces — Twin-Engine Transport

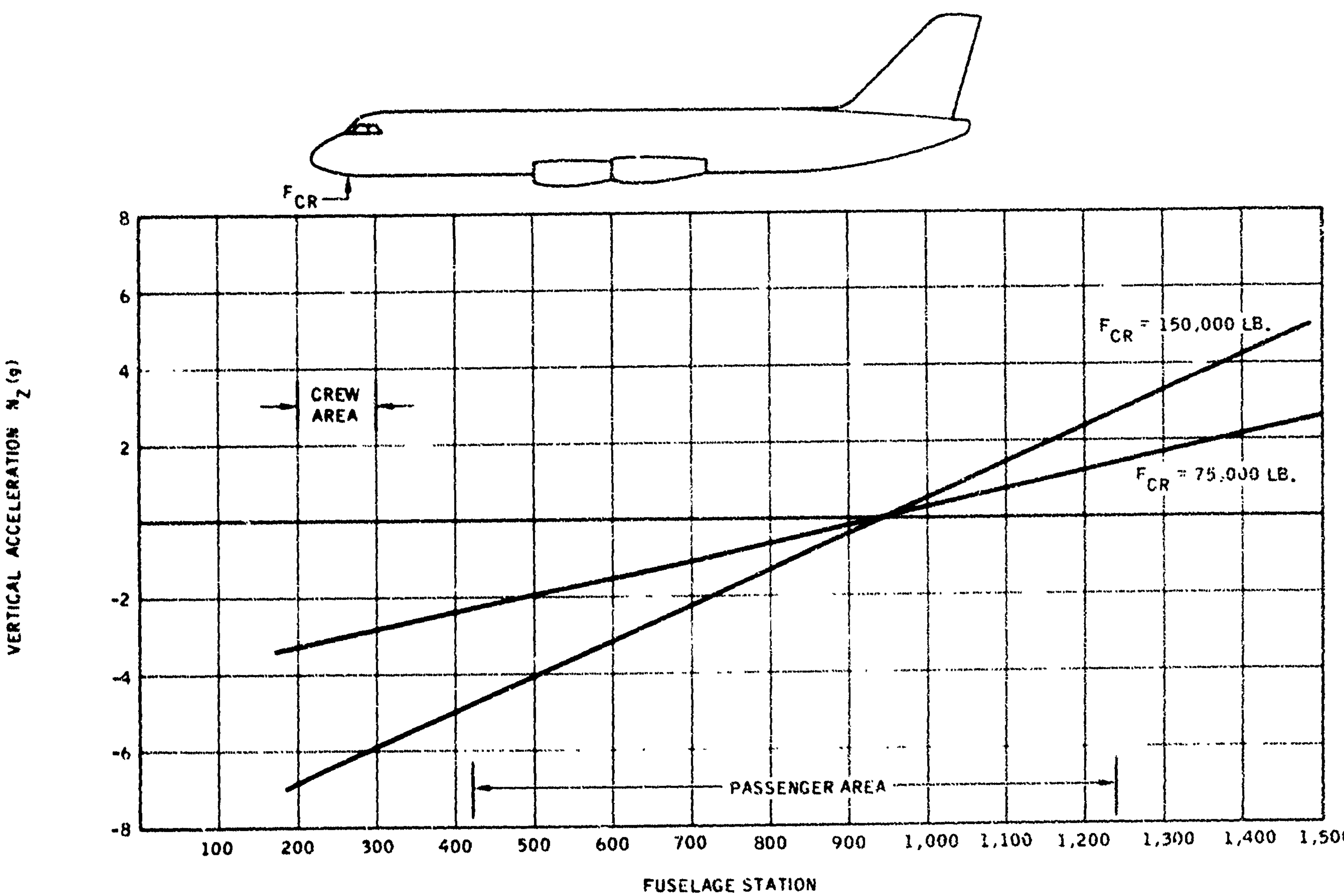


Figure A-6. Vertical Acceleration Due to Nose Crushing Forces — Four-Engine Jet Transport

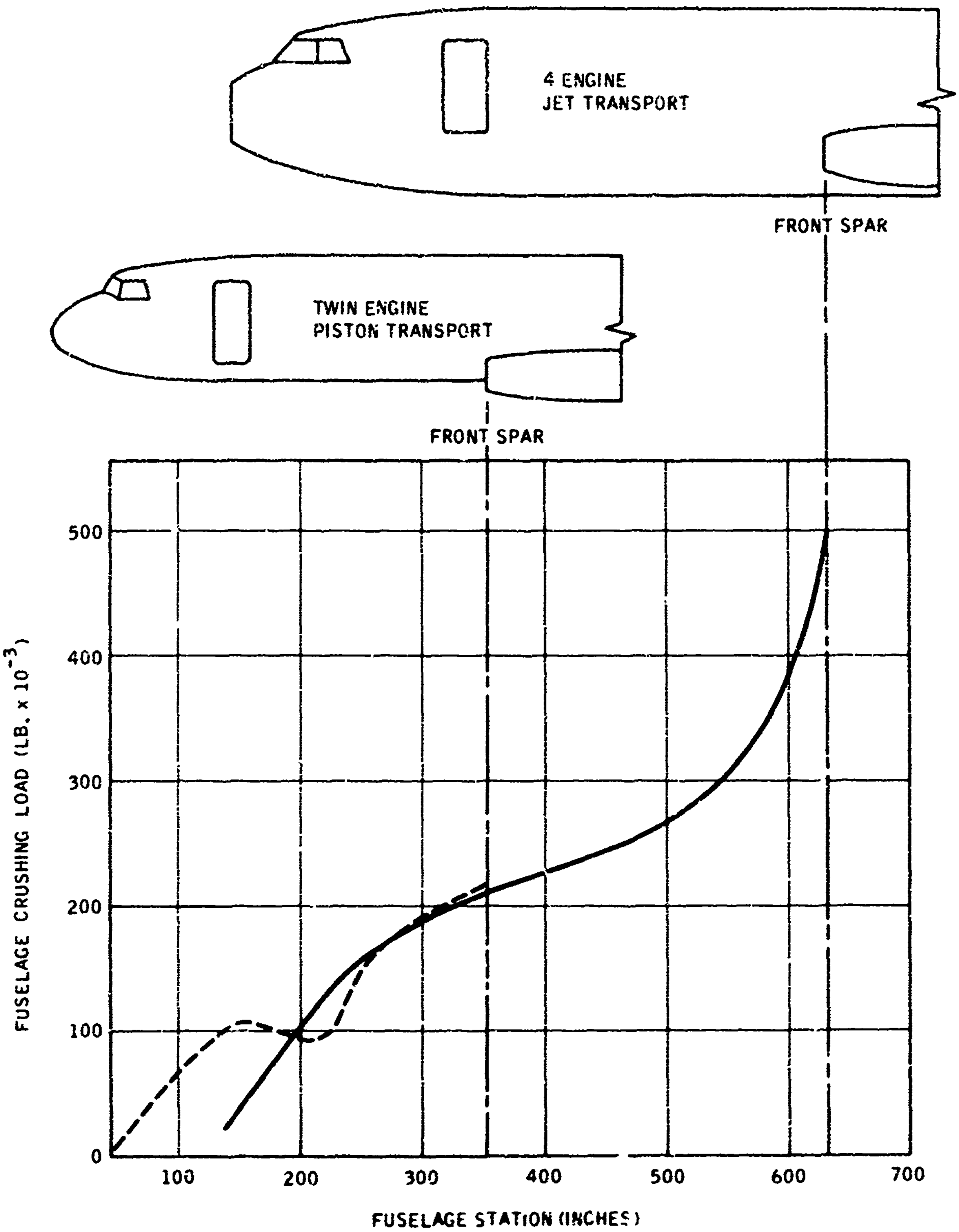


Figure A-7. Allowable Fuselage Crushing Load

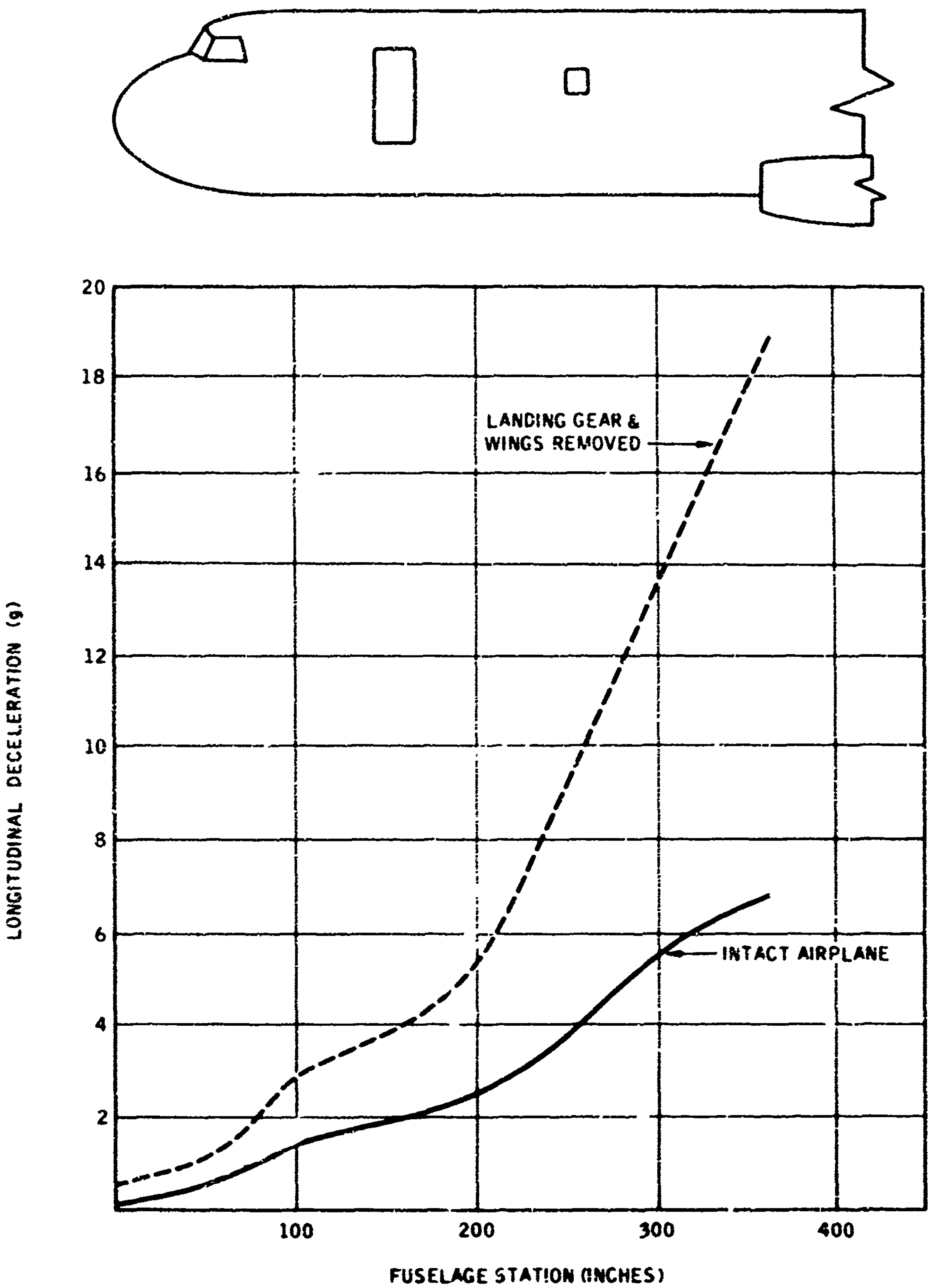


Figure A-8. Deceleration Due to Forward Fuselage Crushing — Twin-Engine Transport

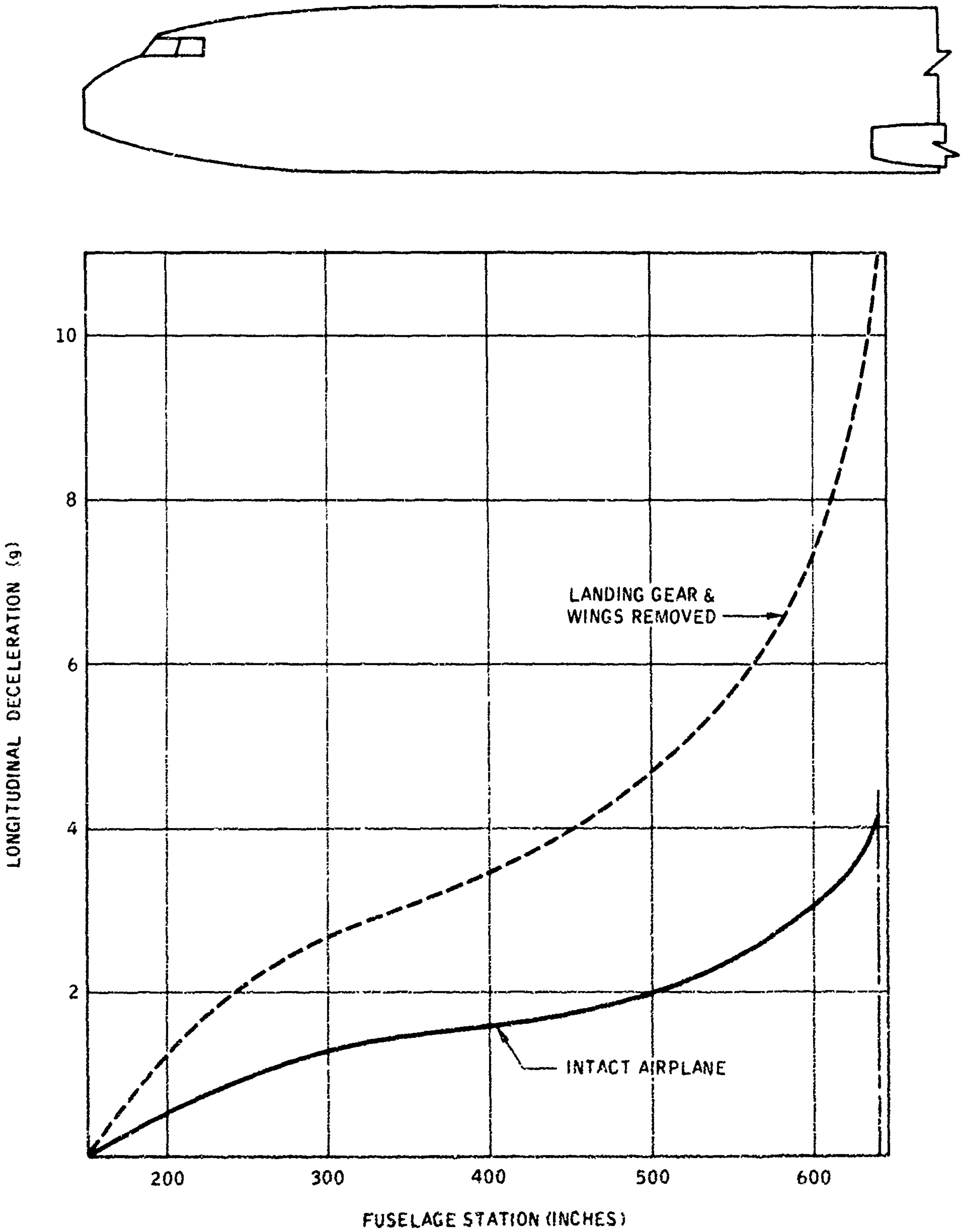


Figure A-9. Deceleration Due to Forward Fuselage Crushing — Four-Engine Jet Transport

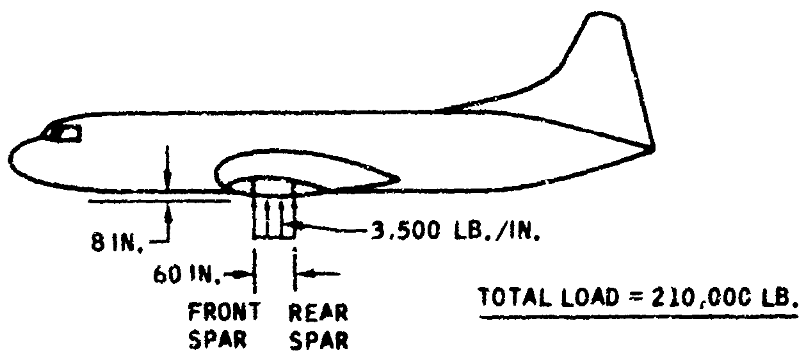


Figure A-10. Vertical Crushing Strength — Twin-Engine Transport

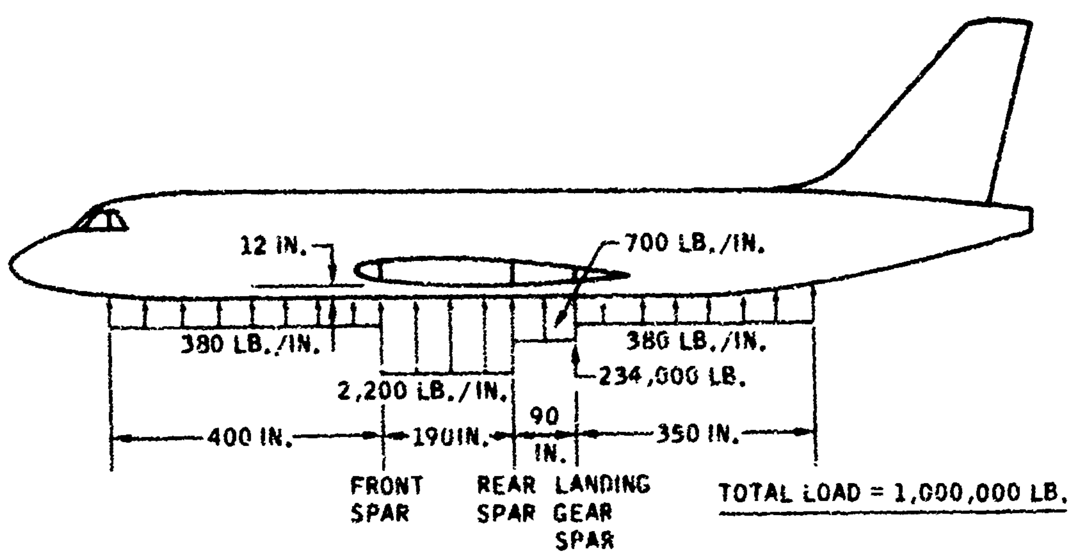
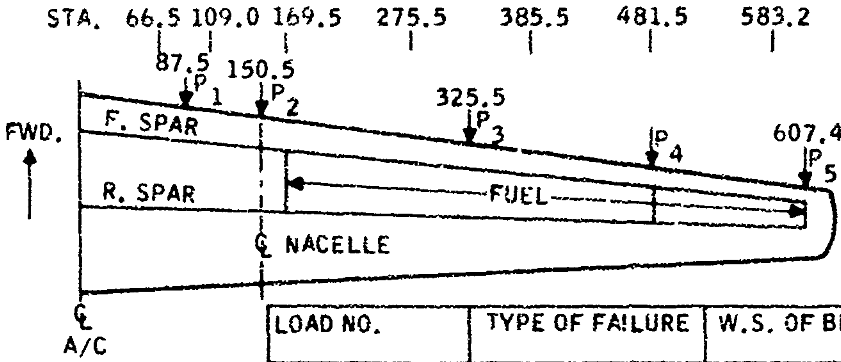
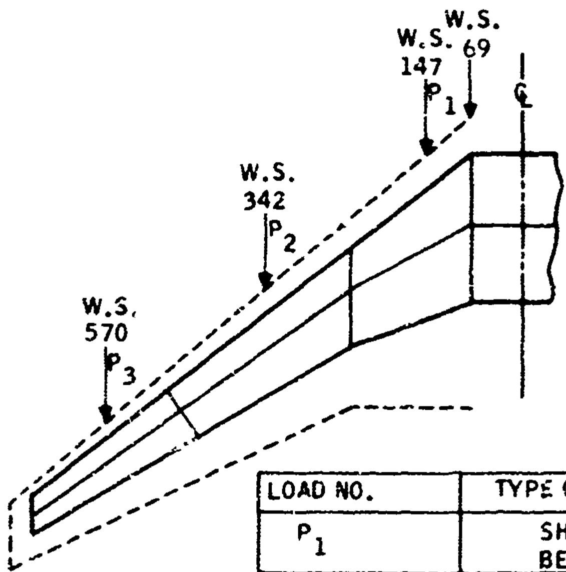


Figure A-11. Vertical Crushing Strength — Four-Engine Jet Transport



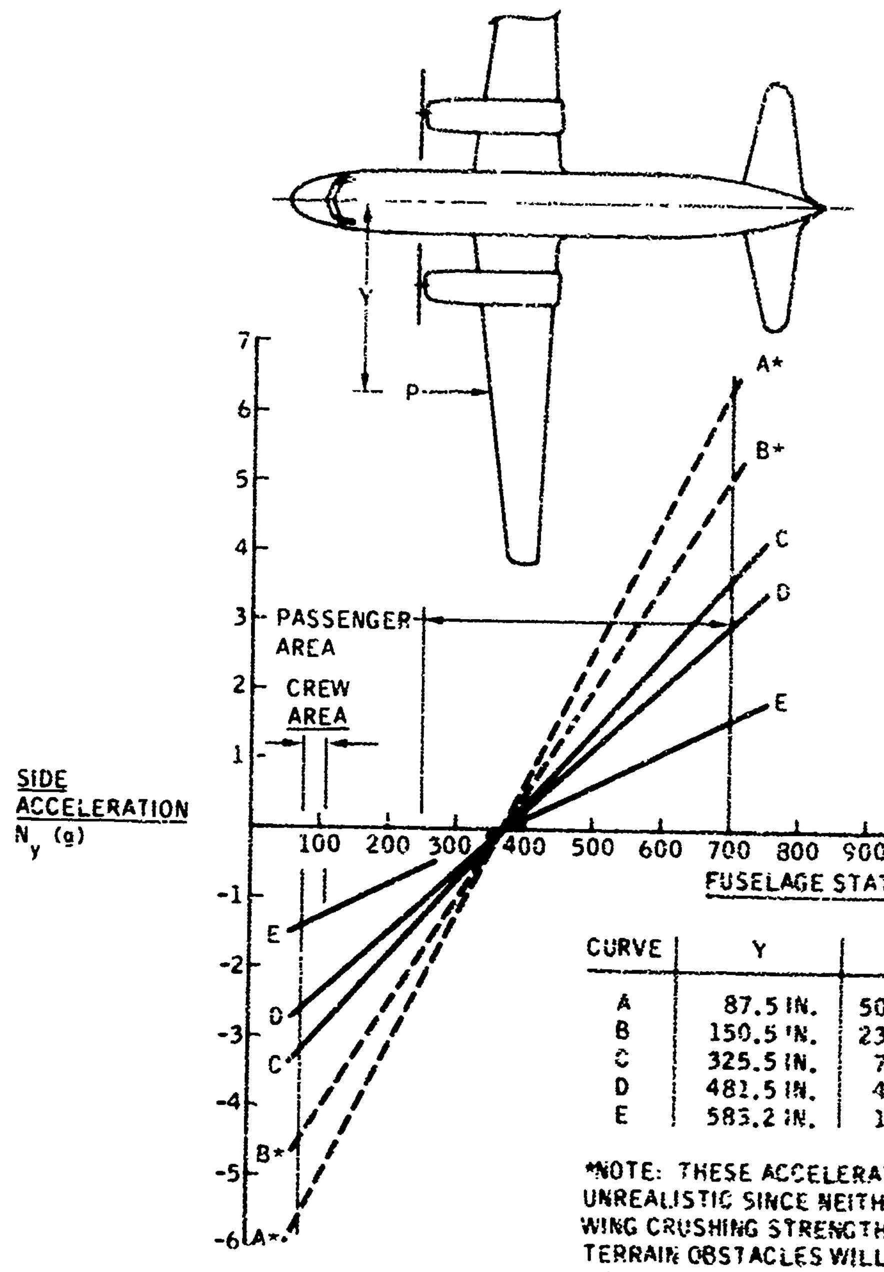
LOAD NO.	TYPE OF FAILURE	W.S. OF BREAK	LOAD AMPLITUDE (LB.)
P_1	SHEAR	87.5	507,000
	BENDING	66.5	948,000
P_2	SHEAR	150.5	463,000
	BENDING	66.5	237,000
P_3	SHEAR	325.5	245,000
	BENDING	66.5	77,000
P_4	SHEAR	481.5	103,000
	BENDING	270.0	43,000
P_5	SHEAR	607.4	45,000
	BENDING	490.0	19,000
FULL-SPAN UNIFORM LOAD.	BENDING	66.5	103,000
HALF-SPAN UNIFORM LOAD.	BENDING	66.5	235,000

Figure A-12. Twin-Engine Transport Wing Chordwise Strength



LOAD NO.	TYPE OF FAILURE	W.S. OF BREAK	LOAD REQ. (LB.)
P_1	SHEAR	69	1,130,000
	BENDING	69	1,630,000
P_2	SHEAR	342	1,070,000
	BENDING	69	466,000
P_3	SHEAR	570	420,000
	BENDING	301	206,500
FULL-SPAN DISTR. LOAD	BENDING	69	500,000
HALF-SPAN DISTR. LOAD	BENDING	69	750,000

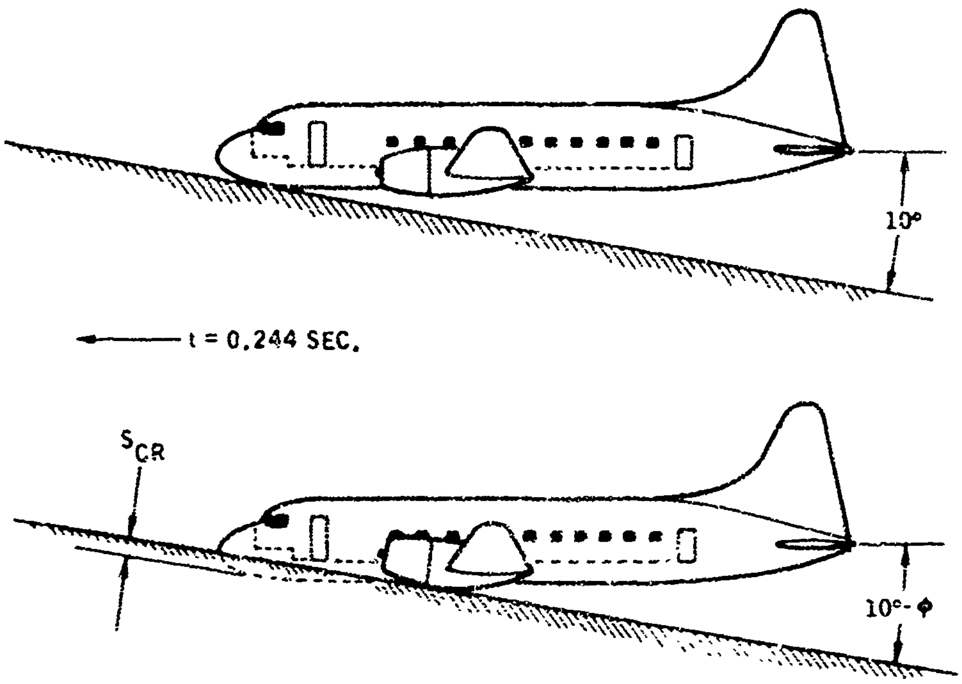
Figure A-13. Four-Engine Jet Transport Wing Chordwise Strength



CURVE	Y	P
A	87.5 IN.	507,000 LB.
B	150.5 IN.	237,000 LB.
C	325.5 IN.	77,000 LB.
D	481.5 IN.	43,000 LB.
E	583.2 IN.	19,000 LB.

*NOTE: THESE ACCELERATIONS ARE UNREALISTIC SINCE NEITHER THE WING CRUSHING STRENGTH NOR MOST TERRAIN OBSTACLES WILL ALLOW THIS MAGNITUDE OF FORCE.

Figure A-14. Effects of Wing Impact and Failure on Airplane Yaw Inertias — Twin-Engine Transport



AIRPLANE PROPERTIES:

GROSS WEIGHT (GW) = 45,000 LB.
ALLOWABLE NOSE FORCE = 35,000 LB.
DISTANCE FROM NOSE FORCE TO C.G. (ℓ) = 25 FT.
PITCH MOMENT OF INERTIA (I_o) = 3.6×10^5 SLUG FT.^{2}

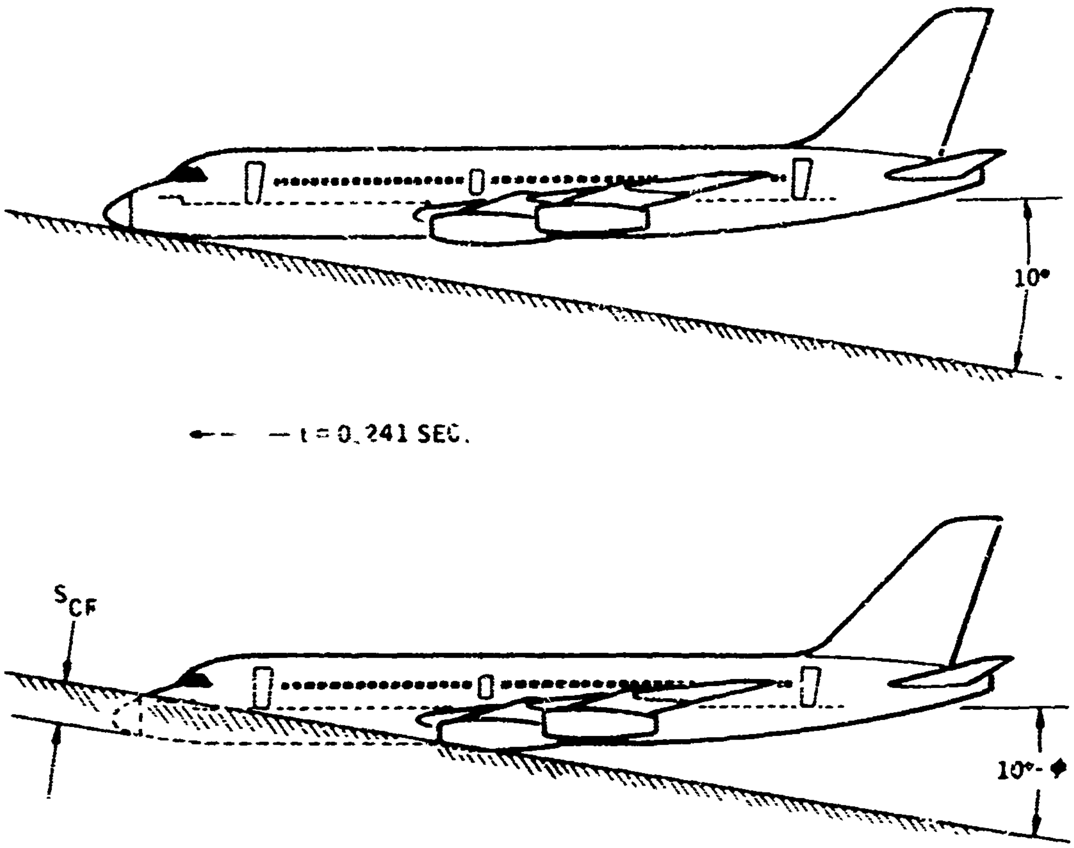
INITIAL CONDITION

DESCENT VELOCITY (V_D) = 21 FT./SEC.
ROTATIONAL VELOCITY (W) = 0

FINAL CONDITION

DESCENT VELOCITY AT C.G. = 14.9 FT./SEC.
NOSE CRUSH DISTANCE (S_{CR}) = 2.56 FT.
ANGLE OF ROTATION (ϕ) = 4.14°
ROTATIONAL VELOCITY (W) = 0.59 RAD./SEC.

Figure A-15. Impact Into a 10° Slope – Twin-Engine Transport



AIRPLANE PROPERTIES

GROSS WEIGHT (GW) = 150,000 LB.
ALLOWABLE NOSE FORCE (F) = 100,000 LB.
DISTANCE FROM NOSE FORCE TO C.G. (ℓ) = 48 FT.
PITCH MOMENT OF INERTIA (I_o) = 2.24×10^6 SLUG FT.^{2}

INITIAL CONDITION

DESCENT VELOCITY (V_D) = 30 FT./SEC.
ROTATIONAL VELOCITY (W) = 0

FINAL CONDITION

DESCENT VELOCITY AT C.G. = 24.8 FT./SEC.
NOSE CRUSH DISTANCE (S_{CR}) = 3.62 FT.
ANGLE OF ROTATION (ϕ) = 3.57°
ROTATIONAL VELOCITY (W) = 0.52 RAD./SEC.

Figure A-16. Impact Into a 10° Slope — Four-Engine Jet Transport

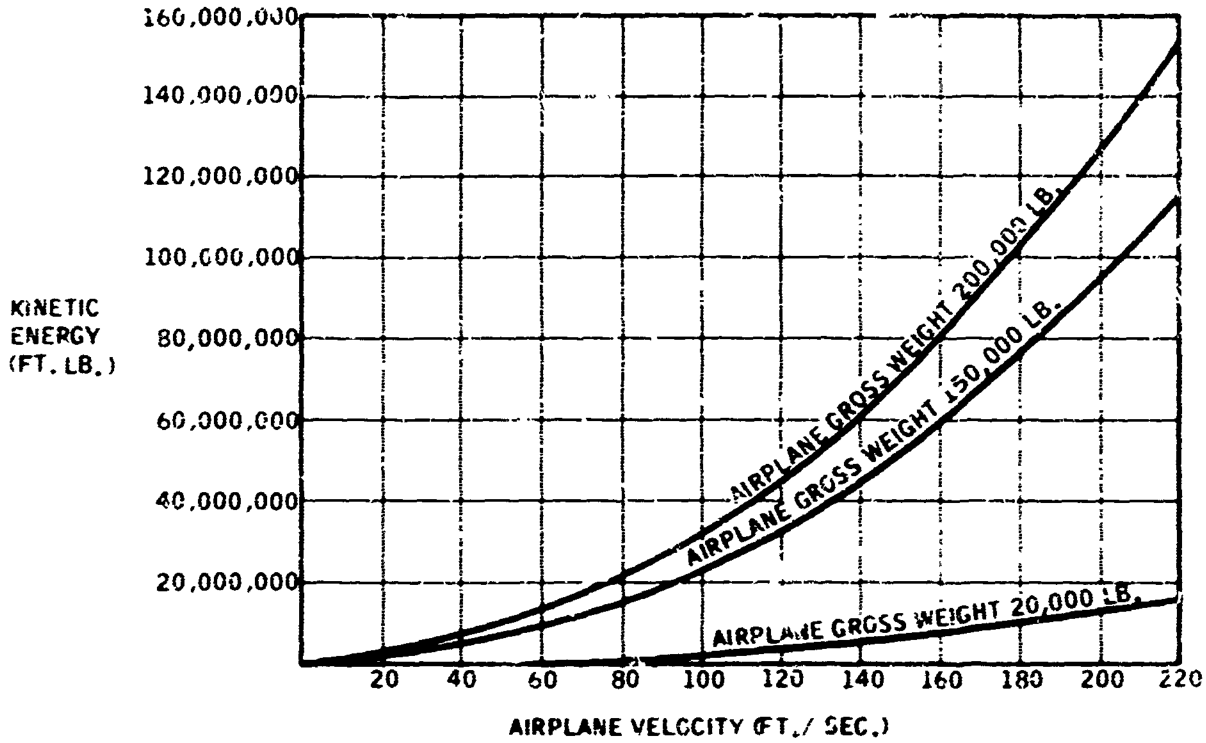


Figure A-17. Kinetic Energy Relationship to Velocity and Gross Weight

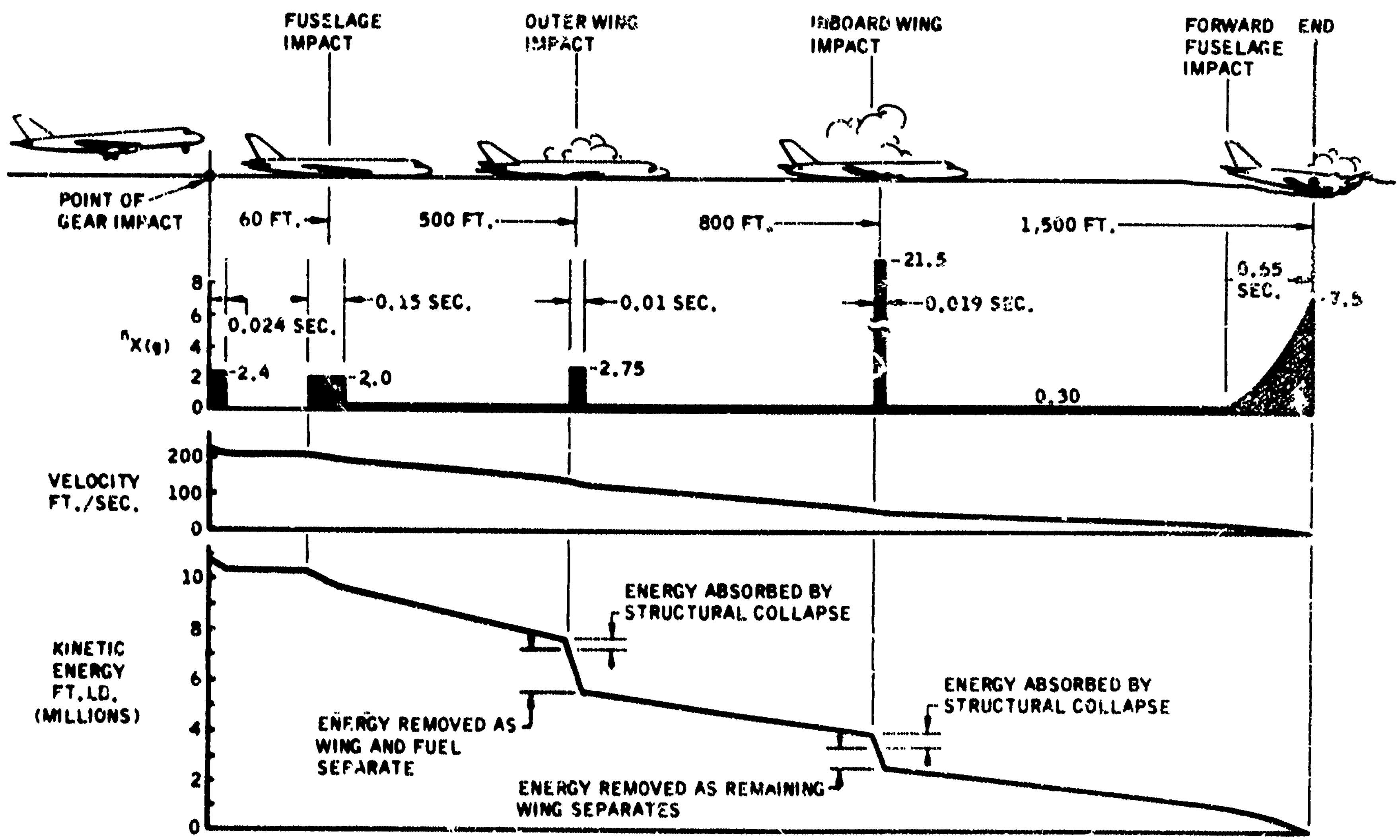


Figure A-18. Crash Sequence — Four-Engine Jet Transport

APPENDIX B | DELETHALIZATION

B.1 OCCUPANT VELOCITY

This study indicates the velocity that an occupant can attain, relative to the seat, during reasonably long airplane decelerations if slack is present. Slack between the occupant and his restraint is not uncommon. Loose seat belts can allow the maximum slack for forward decelerations. Thick, soft seat cushions allow slack during vertical deceleration. Even aft decelerations (or aft facing seats) can involve slack due to seat back cushioning.

Figure B-1 presents occupant velocities relative to the seat assuming an instantaneously-applied longitudinal airplane deceleration, a rigid occupant mass and no friction between the occupant and seat. As the airplane is decelerated and the velocity reduced, the occupant's velocity will not change until he is restrained by the seat. With the velocity equation, $V^2 = 2 a_r s$, occupant-to-seat acceleration, a_r, is the airplane deceleration. And the distance, s, is the distance that the occupant is unrestrained and through which the relative acceleration acts.

B.2 OCCUPANT DECELERATIONS

The preceding study determined the velocity that the occupant can attain relative to the seat or airplane. This relative velocity gives the occupant kinetic energy that must be absorbed by the occupant, seat structure or local airplane structure.

B.2.1 SEAT BELT WEBBING — Seat belt webbing elongations vary with materials and this variation affects occupant decelerations due to slack. Assuming that webbing material is elastic, the occupant declerations will be as shown on Figure B-2.

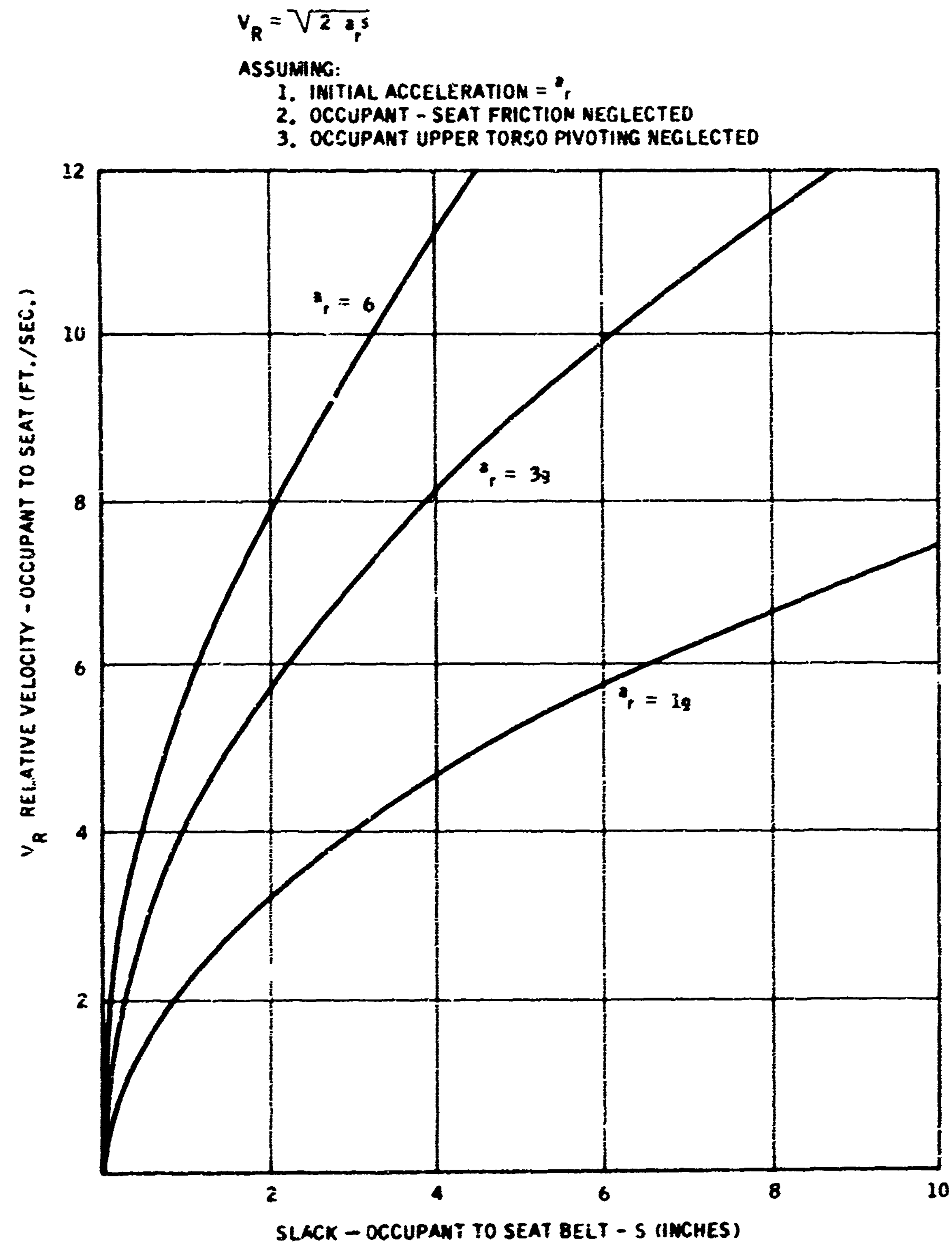


Figure B-1. Relative Velocity of Occupant-to-Seat With Lap Belt Slack

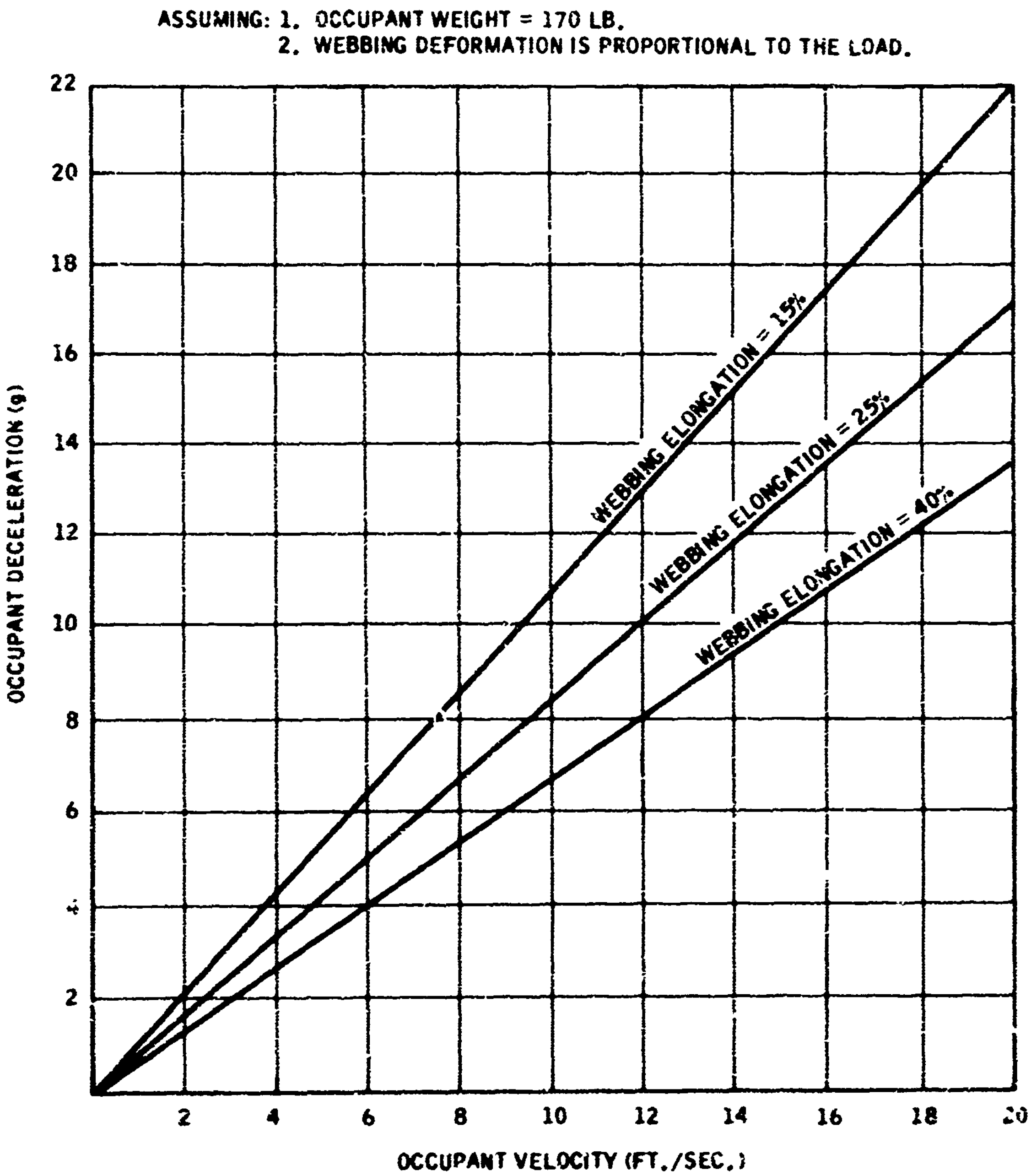


Figure B-2. Seat Belt Webbing Elongation Effects on Occupant Decelerations

The analysis assumes an initial belt length of 3 ft., an occupant weight of 170 lb., and a statically rated webbing strength of 1,500 lb. The belt load, P_B, then equals $V\sqrt{k_b m}$:

Where V = occupant velocity (ft./sec.)

k_b = belt spring constant (lb./ft.) or 1,500 ÷ 1.5e

m = occupant mass in slug ft.^{2} or 170 ÷ 32.2 (slug ft.^{2})

The occupant deceleration then equals P_B ÷ 170. The belt load and occupant deceleration can be computed for variations in belt elongation characteristics and relative velocities.

B.2.2 SEAT STIFFNESS — Reference 7, "Seat Design for Crashworthiness," presents a description of seat stiffness requirements to minimize occupant decelerations due to varying airplane deceleration magnitudes and durations. Although seat stiffness effect is important when related to high airplane decelerations the effect of slack is probably the greater cause of injury and restraint failure during most survivable accidents.

The following analysis indicates the effects of seat stiffness, and particularly the effect of progressive, ductile collapse, on occupant decelerations. The initial assumptions include:

a. Occupant weight = 170 lb.
b. Seat belt slack = 6 in.
c. Airplane longitudinal deceleration = 4g, applied instantaneously.
d. Seat belt webbing elongation = 15%.
e. Seat belt length = 3 ft.
f. The seat is rigid up to static design requirement of 9g.
g. The seat is of single, all-floor-mounted configuration.

From Figure B-1 the occupant velocity relative to the seat is 11.4 ft./sec., due to belt slack. If the seat and floor are rigid the occupant deceleration is 12.3g, determined by the seat belt webbing characteristics from Figure B-2.

The resultant seat attachment loads are shown on Figure B-3 and the total kinetic energy due to occupant-seat relative velocity must be stored in the seat belt, assuming the seat does not fail.

Adding ductile collapse characteristics to the seat reduces the maximum occupant deceleration to 9g. The occupant deceleration will reach 9g as the belt stretches and retain this deceleration as the seat deforms. Figure B-4 shows the ductile seat collapsed configuration and the resultant seat attachment loads. In addition to decreased occupant deceleration, the seat collapse will lower the occupant c.g., reducing the overturning moment at the floor. The kinetic energy due to occupant-seat relative velocity is absorbed during plastic deformation of the seat.

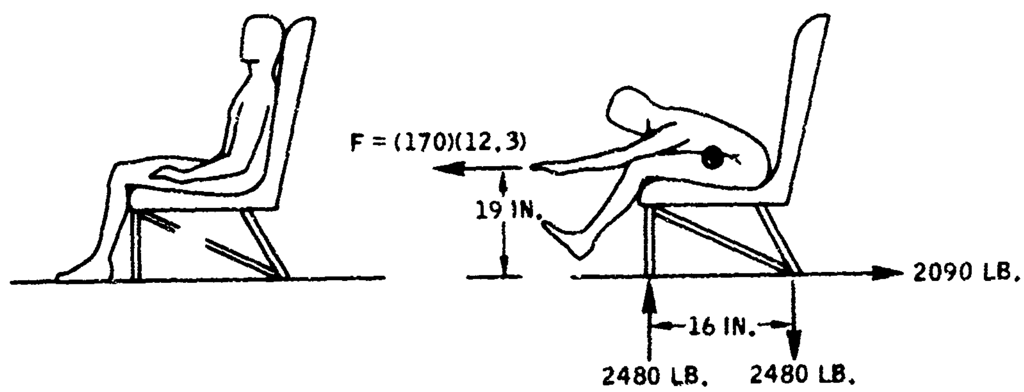


Figure B-3. Seat Attachment Loads — Rigid Seat

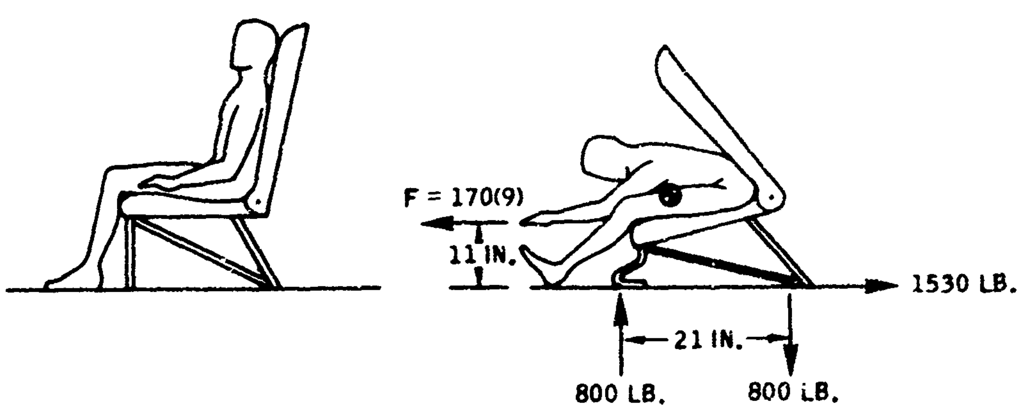


Figure B-4. Seat Attachment Loads — Ductile Seat

As previously mentioned, occupant decelerations can be affected directly by airplane deceleration magnitude and duration if proper seat stiffness characteristics are not provided. A ductile seat can provide an efficient, variable stiffness. Rigidity can be maintained for decelerations up to the static design requirement and flexibility is achieved by plastic collapse as the airplane deceleration peaks above this static requirement.

Figure B-5 presents a conservative seat-airplane deceleration pulse using a ductile seat designed for a static deceleration of 9g forward with the effects of slack and upper torso pivoting neglected. The airplane deceleration reaches 6g, with the seat deceleration reasonably consistent. At t_1 the airplane experiences a short duration peak deceleration of 12g and returns to 6g at t_2. The seat, lagging slightly due to elastic deformation of the seat and floor, reaches 9g and holds the load during plastic collapse. The relative velocity attained between the seat and floor is a maximum as the seat and airplane decelerations cross at Point I. The seat, then must continue to hold the 9g load, even though the airplane deceleration returns to 6g, until the relative velocity is again 0. At t_3 the seat and airplane velocities are equal (Point II). The actual airplane (and seat) velocity relative to the ground is not involved in the seat deceleration nor required energy absorption. Occupant kinetic energy due to velocity relative to the ground must be transmitted through the seat to the airframe, not absorbed in the seat.

Upper torso pivoting can affect the seat stiffness characteristics although, usually, the seat forces produced by slack and pivoting are not applied simultaneously. Some time lag is present between restraint and pivoting, and the occupant deceleration due to seat belt restraint may be considerably reduced by the time pivoting is completed. The most significant effect of pivoting is attained when the upper torso is allowed to rotate to a horizontal position and is decelerated by impact against the lower torso and thighs.

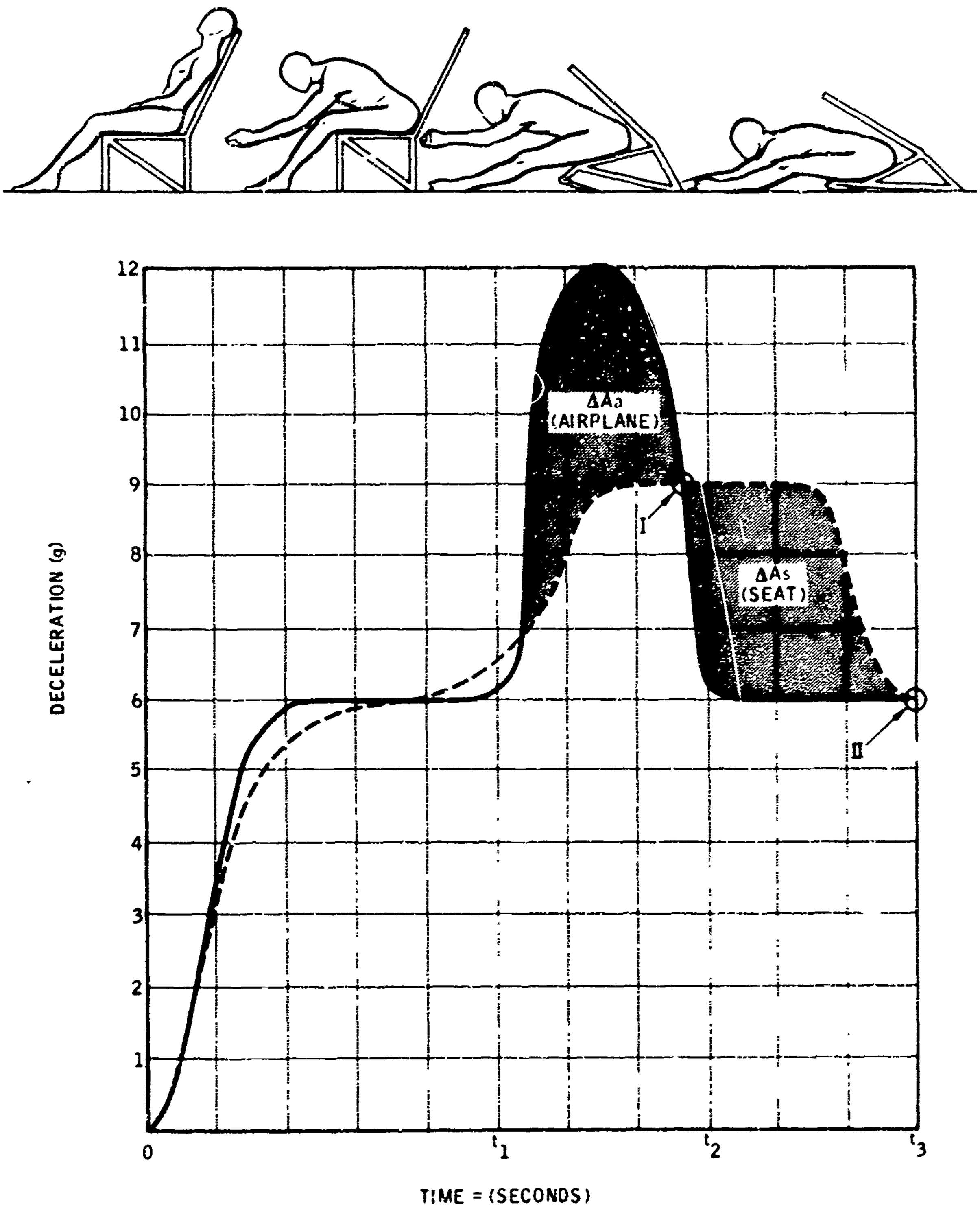
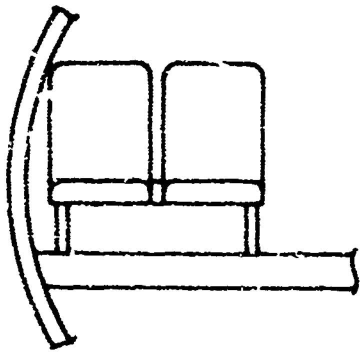


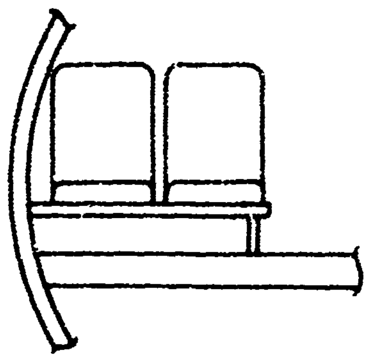
Figure B-5. Airplane and Seat Decelerations — Time History



ADVANTAGES

1. RELATIVE DEFLECTION EFFECTS OF FLOOR AND FUSELAGE SHELL ARE NEGLIGIBLE.
2. SYMMETRY OF PLASTIC COLLAPSE IS PROBABLE.
3. OCCUPANT VERTICAL DECELERATION DISTANCE CAN BE CONTROLLED.

Figure B-6. All-Floor Seat Mounting Configuration



ADVANTAGES

1. SIDE LOAD CAPABILITY AFTER PLASTIC COLLAPSE NOT SIGNIFICANTLY AFFECTED.
2. LIGHTER FLOOR BEAM AND SEAT.
3. OUTBOARD OCCUPANT C.G. CLOSE TO SEAT ATTACHMENT.
4. ENERGY ABSORBTION CAPABILITY DETERMINED BY SEAT PAN AND SIDEWALL STRUCTURE.
5. FLOOR SPACE UNDER SEAT INCREASED.

Figure B-7. Floor-Sidewall Seat Mounting Configuration

B.3 SEAT CONFIGURATION

B.3.1 SEAT MOUNTING CONFIGURATIONS — The two primary seat mounting configurations in use in commercial transport are all-floor and floor-sidewall. Each type has inherent advantages depending on the primary structural configuration of the fuselage and floor. Figures B-6 and B-7 indicate the configurations and advantages of each configuration.

The choice of configuration depends initially on the design requirements of the fuselage. A fuselage that requires a structural floor for shape retention may be lighter with an all-floor seat mounting configuration because of the existing capability for transmitting forward loads from the seats to the fuselage shell. If the floor forward load capability has to be added for the seat forces, the

floor-sidewall configuration will require additional structure. However, the sidewall attachment will allow lighter floor beams.

Whichever configuration is chosen, the objective is to keep the occupant decelerations within human tolerance, to retain the occupant in the seat and to keep the seat attached to the fuselage structure. Handling requirements alone should not be allowed to determine the mounting configuration.

B.3.2 SEAT LEG CONFIGURATION — Forward-acting loads are usually critical for most of the seat structure, including the seat legs. It is important to have a seat leg configuration which provides adequate load paths after the initial failure or collapse has occurred. Probably the most desirable configuration would allow for initial ductile collapse of the forward seat leg or legs.

Figures B-8 and B-9 are examples of leg configurations that illustrate the problems. Figure B-8 shows a ladder truss leg design that will not allow collapse of the forward leg without affecting the aft leg. As the forward leg starts to collapse the horizontal brace applies secondary bending to the aft leg, inducing additional prying at both the seat and floor attachment. Figure B-9 shows a diagonal brace replacing the horizontal brace. Configuration "A" is a tension brace and "B" is a compression brace. These designs have an advantage over that of Figure B-8 in that the forward load is transferred to the floor by an axial member. Configuration "A" of Figure B-9 is the desirable design since collapse of the forward leg will allow the seat to move forward and down without applying secondary bending or compression stresses to the aft legs. Configuration "B," with the compression brace, will not deform in a forward direction until the compression brace fails as a column. This failure then leaves only the aft leg for final restraint.

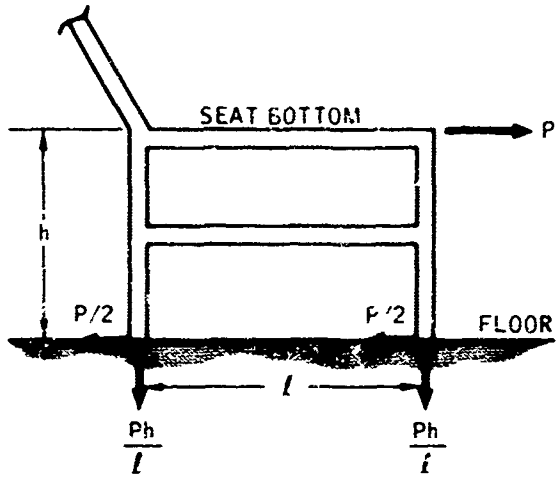


Figure B-8. Seat Leg Configuration — Forward Load Transfer by Shear

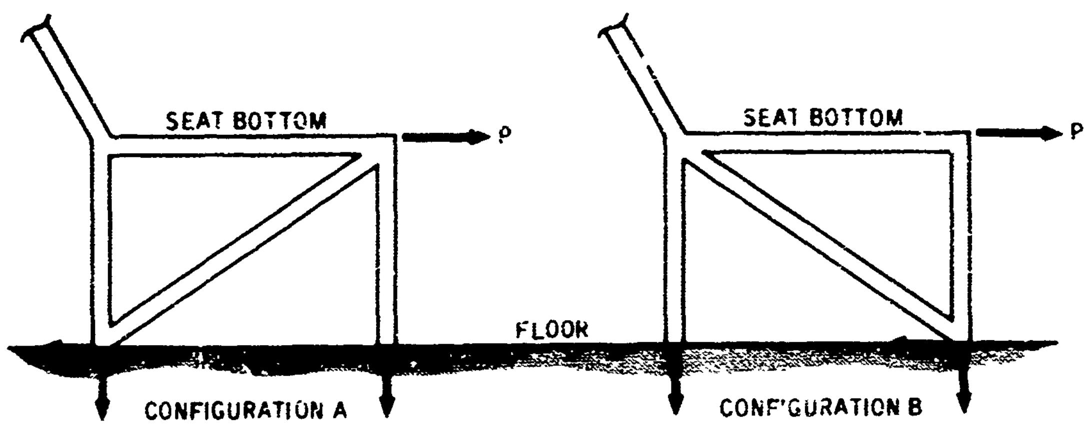


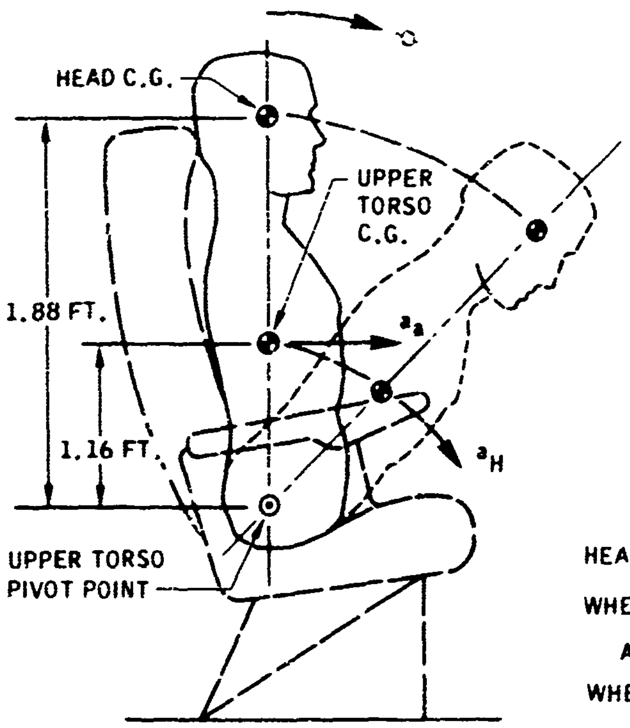
Figure B-9. Seat Leg Configuration — Truss Type

B.4 HEAD IMPACT

B.4.1 IMPACT VELOCITIES — As longitudinal decelerations are applied to the occupant, the upper torso pivots about the seat belt. Occupant injuries occur as the head strikes the seat in front if the structure does not yield, reducing the force applied to the occupant.

The analysis to determine tangential head velocity (V_H) is based on the equations and assumed upper torso characteristics shown below, with the results plotted on Figure B-10.

Head Impact Analysis



UPPER TORSO WEIGHT = 100 LB.
OCCUPANT HEIGHT = 6 FT.
OCCUPANT WEIGHT = 170 LB.

HEAD VELOCITY $(V_H) = 1.88\,\omega$ FT./SEC.

WHERE ω = UPPER TORSO ANGULAR VELOCITY

AND $\omega = \sqrt{\omega\ \text{INITIAL} + 2\Delta\theta\,\alpha\ \text{AVE}}$

WHERE α = UPPER TORSO ANGULAR ACCELERATION

$$\alpha = \frac{a_H}{1.16} = 0.86\ a\ \text{AIRPLANE}\ \cos\theta$$

Two conditions of initial position are assumed, as indicated. Figure B-10(a) is the velocities attained with the occupant in an upright position initially and Figure 10(b) assumes the initial position reclined 38 deg. Both conditions assume a constant horizontal acceleration of 9g and Figure B-10(b) includes an additional curve to indicate the effects of a 4.5g downward acceleration applied with the 9g horizontal acceleration.

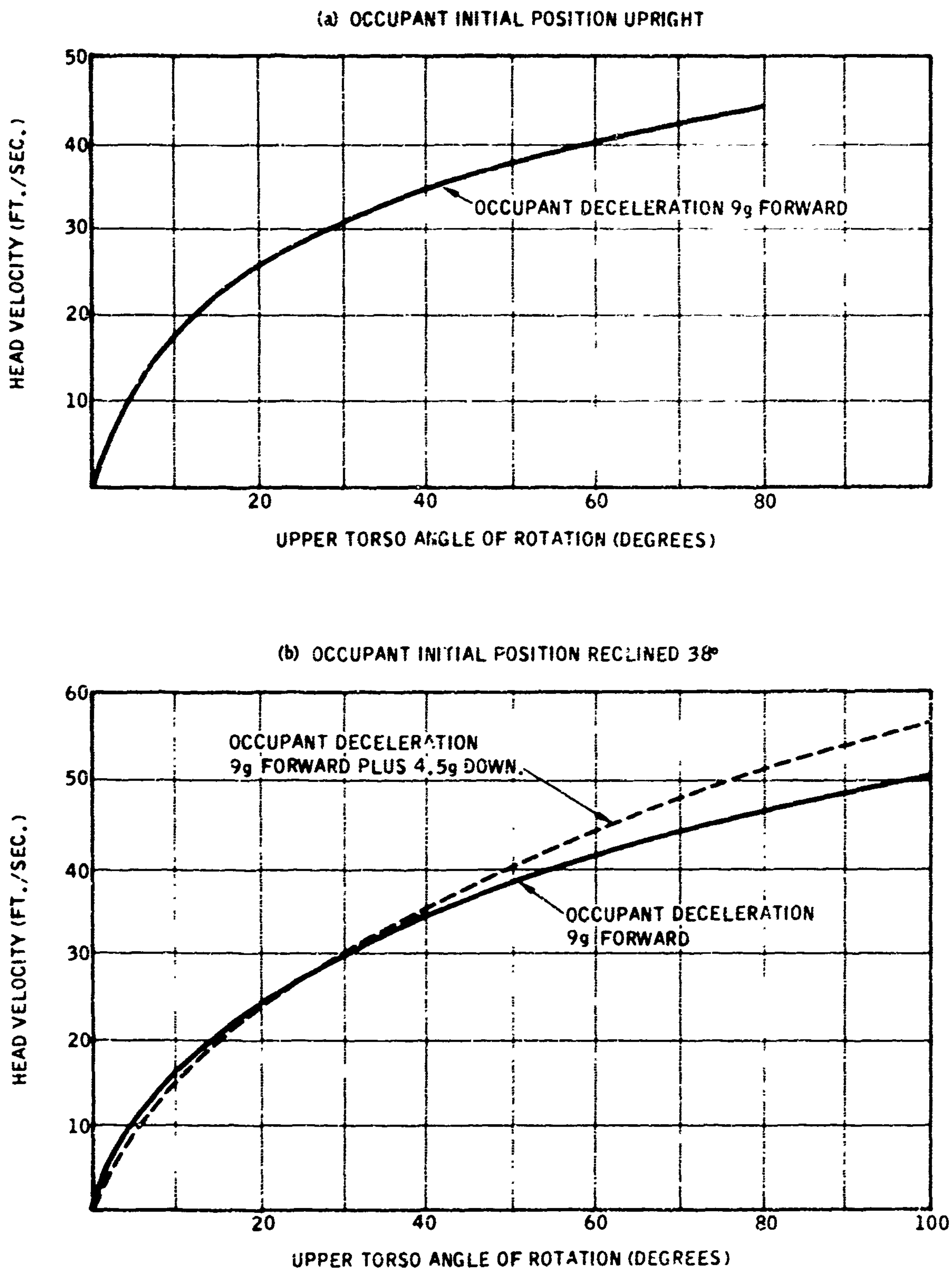
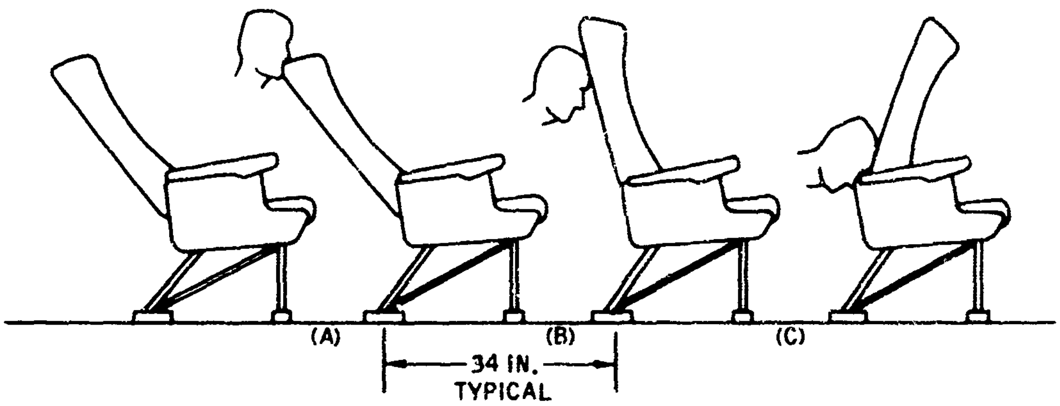


Figure B-10. Head Velocity Due to Upper Torso Pivoting



(A) INITIAL OCCUPANT POSITION 38° RECLINE, NON-BREAKOVER SEAT BACK RECLINED 38° IMPACT VELOCITY 41 FT./SEC.

(B) INITIAL OCCUPANT POSITION 38° RECLINE, NON-BREAKOVER SEAT BACK UPRIGHT – IMPACT VELOCITY 47 FT./SEC.

(C) INITIAL OCCUPANT POSITION 38° RECLINE, BREAKOVER SEAT BACK – IMPACT VELOCITY 51 FT./SEC.

Figure B-11. Head Impact Due to 9g Occupant Deceleration

Figure B-11 indicates the probable head impact locations, and velocities. with a typical 34-in. seat spacing arrangement. The impact velocities noted are due to the 9g horizontal acceleration and do not include the 4.5g downward acceleration effects.